Towards the New Vernacular
A Study on Climate-Responsive Buildings in Informal Cairo

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Abstract

In 2019 buildings accounted for an estimated 35% of total global energy use and almost 38% of energy-related greenhouse gas emissions, and this number could even triple by 2050 due to several trends, one of which is the increased access for billions of people in the global South to adequate housing and electricity. When globalisation and technological development are confronted with rapid urbanisation, climate change, and the provision of adequate living conditions, vernacular and traditional architecture still occupies a marginal position in science.

By taking Cairo as a case study, this research builds up on the lessons learned from local and vernacular architecture. Wants to find and test design strategies and passive systems that work in Cairene's climate. While focusing on the architecture of informal apartment blocks, it seeks to what extent it can meet the end user's thermal comfort expectations while being energy and environmentally sound. Furthermore, linking the meta topics of vernacular architecture, thermal comfort, and energy consumption brings new insights into the discussion about sustainable urban development in hot and dry climates.

With a theoretical and empirical study, the characteristics, and the thermal and energy performance of three Cairene buildings are discussed and compared. An optimisation study of an informal building is conducted. Different strategies, systems, and relative options to increase comfort and decrease energy demand are explored. In addition, some of the well-performing options are further analysed, and through a cost-benefit and a future climate scenario analysis, the consequences of their implementation are discussed. Several sensitivity studies are carried out to find which systems and strategies might affect the end user's comfort of the informal building. Furthermore, by digitally re-locating the analysed informal building into different urban scenarios, the elements that influence the building performance are further analysed with the help of parametric analysis. This last point leads to a series of recommendations that might be useful when designing a new building within this context or when retrofitting an existing one. Furthermore, limitations and outlook for further research are discussed.

A general summary of learnings is made in the closing remarks, and an answer to the research is given. A reflection about the research process and its outcomes is carried out, and the connection to the overarching topics of adaptation and mitigation in the Egyptian context is made.

Keywords: Informality, Thermal Comfort, Hot and Dry Climates, Design Strategies, Passive Systems, Building Performance Simulation

Im Jahr 2019 entfielen schätzungsweise 35% des weltweiten Gesamtenergieverbrauchs und fast 38% der energiebedingten Treibhausgasemissionen auf Gebäude. Diese Zahl könnte sich bis 2050 aufgrund mehrerer Trends verdoppeln oder sogar verdreifachen, unter anderem durch den verbesserten Zugang von Milliarden von Menschen im globalen Süden zu angemessenem Wohnraum und ausreichender Stromversorgung. Doch wenn Globalisierung und die technologische Entwicklung auf die rasante Urbanisierung, den Klimawandel sowie adäquaten Lebensbedingungen stoßen, nimmt die volkstümliche und traditionelle Architektur in der Wissenschaft noch immer eine Randposition ein.

Am Beispiel von Kairo baut diese Untersuchung auf den Erfahrungen mit lokaler und volkstümlicher Architektur auf. Ziel ist es, Entwurfsstrategien und passive Systeme zu finden und zu testen, die unter den klimatischen Bedingungen Kairos funktionieren. Die vorliegende Arbeit konzentriert sich auf die Architektur informeller Wohnblocks und untersucht, inwieweit diese die Erwartungen der Endnutzer an den thermischen Komfort erfüllen und gleichzeitig energie- und umweltverträglich sein kann. Darüber hinaus bringt die Verknüpfung der Metathemen volkstümliche Architektur, thermischer Komfort und Energieverbrauch neue Erkenntnisse in die Diskussion über nachhaltige Stadtentwicklung in heißen und trockenen Klimazonen.

Anhand einer theoretischen und empirischen Studie werden die Merkmale sowie die thermische und energetische Leistung von drei kairischen Gebäuden diskutiert und verglichen. Des Weiteren wird eine Optimierungsstudie für ein informelles Gebäude durchgeführt, dabei werden verschiedene Strategien, Systeme und relative Optionen zur Steigerung des Komforts und zur Senkung des Energiebedarfs untersucht. Einige der gut funktionierenden Optionen werden im Anschluss weiter analysiert. Anhand einer Kosten-Nutzen-Analyse und unter Berücksichtigung eines zukünftigen Klimaszenarios werden die Folgen ihrer Umsetzung diskutiert. Es werden mehrere Sensitivitätsstudien durchgeführt, um herauszufinden, welche Systeme und Strategien sich auf den Komfort des informellen Gebäudes für den Endnutzer auswirken könnten. Darüber hinaus werden die Elemente, die die Leistung des Gebäudes beeinflussen, mit Hilfe parametrischer Analysen weiter analysiert, indem das analysierte informelle Gebäude digital in verschiedene urbane Szenarien eingefügt wird. Dieser letzte Punkt führt zu einer Reihe von Empfehlungen, die beim Entwurf eines neuen Gebäudes in diesem Kontext oder bei der Nachrüstung eines bestehenden Gebäudes nützlich sein könnten. Schließlich werden Einschränkungen und Perspektiven für die weitere Forschung diskutiert.

In den Schlussbemerkungen wird eine allgemeine Zusammenfassung der Erkenntnisse vorgenommen und eine Antwort auf die Forschungsfragen gegeben. Es wird eine Reflexion über den Forschungsprozess und seine Ergebnisse durchgeführt sowie eine Verbindung zu den übergreifenden Themen Anpassung und Mitigation im ägyptischen Kontext hergestellt.

1. Introduction

1.1. Background, Problem Statement and Objective of the Study

Just until the Twentieth Century, all over the world, buildings were built according to the local climate, resources, knowledge, and users' needs. On the other hand, by looking at contemporary architecture on a global scale, the building industry has moved towards an internationalised style of buildings that promotes the use of machines, energy, and resources during the last century. In 2019 buildings accounted for an estimated 35% of total global energy use and almost 38% of energy-related greenhouse gas emissions (U.N. Environment Programme, 2020). As the Intergovernmental Panel on Climate Change points out, this number could double or even triple by 2050 due to several trends, one of which is the "increased access for billions of people in developing countries to adequate housing and electricity" (IPCC, 2014).

When globalisation and technological development are confronted with rapid urbanisation, climate change, and the provision of adequate living conditions, new measures and innovative solutions - at different urban scales - must be found and implemented to decrease energy consumption and greenhouse gas emissions. In the last decades, both in practice and in the research fields, a lot has been done and written about sustainable and energy-efficient buildings, as well as on the role that passive design has in the field of sustainable development (see e.g. Economidou et al., 2011; Kristinsson, 2012; Lavafpour, 2012; Roaf, Crichton, & Nicol, 2005; Ruby & Ruby, 2020). Nevertheless, the study of vernacular, local, and traditional architecture still occupy a marginal position in the field of architectural research (Asquith & Vellinga, 2006). We hypothesise that while searching for new solutions to tackle some of the global issues of our era locally, the study of buildings built by our predecessors might be of great help on this matter. If we think about it, isn't that true that many of those buildings have been able to pass the test of time sustainably and have been able to comfort their inhabitants before the era of air-conditioning and cheap-fuel heating by using adaptable and low-technology solutions? (Lavafpour, 2012; Roaf et al., 2005) With this in mind, this study aims to investigate the possible role of traditional architecture's design principles in the contemporary urban context and the extent of its use for meeting the end user's thermal comfort expectations while having a low energy demand. This thesis will address the research questions: *To what extent is it possible, by learning from vernacular strategies, to optimise the contemporary architecture in dry and hot climates to meet the end user's thermal comfort expectations while being environmentally sound?*

1.2. Research Focus: Cairo

With its estimated 18-20 million inhabitants and a population density that can exceed 90.000 people per square kilometre, Cairo is not only the first mega-city in the African continent but also one of the places where the results of urbanisation are more visible (Ibrahim, 2003; U.N. Habitat, 2011). According to the German Advisory Council on Global Change (WBGU), providing adequate housing and living conditions, offering long-term access to infrastructures, and covering social needs are some of the most impelling concerns that the city has (2016).

Cairo's dry and hot climate (BWh by Köppen-Geiger climate classification) leads to challenges that urban dwellers experience daily and are related to health and indoor comfort. The multi-storey apartment blocks where most households live (about 88%) are generally poorly insulated against hot temperatures, hardly shaded, and badly ventilated (U.N. Habitat, 2011; WBGU, 2016). Furthermore, the energy supply in the residential sector has found itself in a crisis for years; even though 99 per cent of the buildings are connected to the public electricity network, between 11 and 22 per cent of households experience constant power interruptions (U.N. Habitat, 2011). As pointed out by the Ministry of Electricity and Renewable Energy, the residential sector in Egypt was responsible in 2018 for about 48 per cent of the share of energy consumption (60.115 GWh). This number, which was about 40 per cent in 2009 (47.431 GWh), is steadily growing due to the "expansion of residential compounds [...] and the widespread use of domestic appliances, especially the air conditioners in the summer" (Egyptian Electricity Holding Company, 2011, 2019b). Over the next years, the city is expected to grow at a 2,11 per cent rate, with 65% of the population living in "unplanned" settlements; therefore, finding sustainable and holistic solutions is of primary importance (U.N. Habitat, 2011).

Little research has been published[1] to date on passive or active energy-saving approaches in the building sector in Cairo, and the government has not given any incentives so far for specific programs in the field (WBGU, 2016). Recently, the study *The practice and politics of urban climate change mitigation and adaptation efforts: the case of Cairo,* underlined that “there is a huge knowledge gap in the Middle East and in Egypt when it comes to research efforts related to climate change with a focus on the built environment” (Dabaieh, Maguid, Abodeeb, & El, 2021). Building codes and standards (including recommendations and guidelines that are implementable in different regions or communities), which may have a significant role in the outcomes related to thermal behaviour of buildings and energy consumption, have yet to be implemented in Egypt (Shamseldin, 2017; Wael Sheta, 2018).

So far, it has already been demonstrated that to reach environmental performance, one of the best options is to improve energy efficiency, and "simulation [...] prove to be very effective while decision making amongst various available options” (Dakwale, Ralegaonkar, & Mandavgane, 2011). When looking at the Arab Republic of Egypt, scholars have done research that includes simulations, but most of the works focus either on the energy consumption of existing buildings or the outdoor comfort related to the urban form (Abdellatif, 2018; Edeisy & Cecere, 2017; Mohamad Fahmy & Sharples, 2009; Mahmoud, Fahmy, Mahdy, Elwy, & Abdelalim, 2020; Mousa, 2016; Samaan, Farag, & Khalil, 2018). Vernacular architecture has been researched in Egypt and Cairo (especially by Hassan Fathy, see, for example, *Natural energy and vernacular architecture*, 1986). Still, even if very enlightening, his experiments have been limited to an architectural form that has decidedly less in common with the one found in the contemporary urban fabric. Therefore, this research aims to find building design strategies and passive strategies that can be implemented in the urban and "unplanned" or “informal” contexts. Furthermore, linking the meta topics of vernacular architecture, thermal comfort, and energy consumption brings new insights into the discussion about sustainable urban development in hot and dry climates.

[1] In the last two decades, the number of environmental design courses in Egyptian universities has increased. Scholars understand the importance of decreasing GHG emissions and energy consumption, and the increasing number of academic publications with this focus can demonstrate this. Nevertheless, as it also happens in universities worldwide, many studies remain accessible only in situ (Edeisy & Cecere, 2018).

1.3. Behind the Title

When researching in this context, one can be overwhelmed by the use of words that almost interchangeably are used when describing *buildings* (green, traditional, vernacular, heritage contemporary, modern, climate-adaptive, bioclimatic, climate-responsive, low-tech, low-energy, energy-efficient, etc.), *strategies*, *technologies*, *features* and *systems* (passive, active, hybrid, etc.), and *urban settlements* (formal, informal, slums, unplanned, marginalised, unsafe, etc.). As a starting point for understanding the research and its boundaries, it might be helpful to clarify some of the terms that recur in this study. Therefore, while also explaining the title of this study – *Towards the New* ***Vernacular*** *– a Study on* ***Climate-Responsive Buildings*** *in* ***Informal Cairo*** – the following are the most important definitions.

When we refer to **vernacular architecture**, we follow the definition given by Paul Oliver in its opus Magnus, *the Encyclopaedia of vernacular architecture of the world*:

> *Vernacular architecture comprises the dwellings and all other buildings of the people. Related to their environmental contexts and available resources, they are customarily owner- or community-built, utilising traditional technologies. All forms of vernacular architecture are built to meet specific needs, accommodating the values, economies and ways of living of the cultures that produce them.* (1997a, p. xxiii)

Although we will touch upon and assess the energy demand of three buildings in chapter five, the primary goal of the building optimisation process in the sixth chapter is to understand how thermal comfort might be improved. It is implicitly meant that, by optimising a building solely with passive systems, its energy consumption will be reduced while increasing thermal comfort. Therefore, the definition of **climate-responsive buildings** is taken from the definition of climate responsive design made by Looman:

> *Climate-responsive design embraces a strategy in building design where it extents bioclimatic design principles of form and envelope design to structural and architectural elements that actively harvest potential energy flows. Climate-responsive design is not primarily about minimising the energy demand of buildings. It is about creating a comfortable and healthy building that benefits from the potential of the natural energy resources in the built environment.* (Looman, 2017, p. 109)

The definition of **informal** (used in the Cairene's context) is borrowed by David Sims' book *Understanding Cairo: the logic of a city out of control*. Informal settlements are not described as slums or shantytowns, but rather as the "*results of extra-legal urban development processes […] that exhibit a complete lack of urban planning or building control*" (Sims, 2012, p. 95).

Other recurring terms used are **design strategies** and **passive systems**. When talking about **design strategies**, we take the approach used by Lavafpour. With strategies, we intend the architectural principles and design criteria with an overarching scope within a specific context. In hot and dry climates, design strategies include, for example, minimisation of solar gains and conductive heat flow, interception of solar gains, promotion of ventilation (2012). With the term **passive systems**, we intend systems that do not require any energy input for their functioning and are implemented to follow selected strategies, as mentioned by Roaf, Crichton & Nicol (2005, pp. 184, 201). An overhang, for example, is in this sense a passive shading system strategically implemented to intercept solar gains.

1.4. Conceptual Framework and Thesis Structure

Before we start digging into the characteristics of the Egyptian Capital and its buildings, the first step that we take in this research is related to the choice of tools used for evaluating buildings' energy and thermal performance. In the chapter *Evaluation of Building Performance Simulation Software*, three digital tools are compared following a multi-criteria evaluation analysis. Special attention is given to the aspects related to tool accuracy and validity. Therefore, while the software Sefaira and DesignBuilder have been already validated, a partial validation of the software Primero-Comfort following the ASHRAE Standard 140 is made. According to the results of this analysis, both Primero-Comfort and DesignBuilder showed to be suitable for this research and were chosen. The first one is an excellent alternative to get early-phase design ideas and results and test models within a short amount of time. The second one has been evaluated as the best option for in-depth studies requiring a lot of flexibility with input data and output options.

The third and fourth chapters aim to give the reader an overview of the Egyptian Capital and give a general description of the framework in which this experimental research is carried out. Studying how an urban landscape has developed throughout the years, understanding how the geography, the climate and the socio-economic conditions of its inhabitants have been influencing this development, is a crucial point for recognising the status quo and for critically reflecting any possible vision that might be inspirational for building the future. In the chapter *Cairo: Geography and Climate Analysis*, after a short introduction about the Egyptian geography, historical data of the Republic is summarised, and projections for future climate are explored. With the help of room simulation, an insight into future climate trends and their possible consequences on thermal comfort is given. The chapter *Cairo: a Short Introduction to its Informal Urban Development* provides an overview of the urban development that transformed the Egyptian Capital into one of the world's biggest and densely populated areas. By investigating the city's recent history, the magnitude of importance that informal buildings have in the Cairene urban context is discussed, and a reflection on their advantages and disadvantages is done.

The fifth chapter, *Cairo: Chasing the Vernacular*, is where the building scale is the focus. With a theoretical and empirical study, the characteristics and the thermal and energy performance of three Cairene buildings are discussed and compared. Looking at the circumstances in which Manzil Zaynab Khatun (built in the XV Century), Hamed Said house (built in 1942), Abdullah's building (built informally around 2014) were built will help understanding how climatic conditions, household's needs and customs, local knowledge, technologies, and resources played a role in the building process. It is argued that Abdullah's building – within its limitations - might be considered the contemporary incarnation of a Cairene vernacular building. Climate-responsive features are analysed in each building. In the section *Strategies and Systems for Enhancing Thermal Comfort*, the design strategies (e.g. minimise solar gains, promote ventilation) and the passive systems (e.g. compact volume, thermal mass, insulated roof) are summarised and discussed. In the empirical study, the thermal and energy performance of the three buildings is assessed with the help of a Building Performance Simulation Software. All primary inputs, differences between the models, and the expected results are precisely described. The outcomes of the tests (thermal performance, heat and cooling demand of the buildings, sensitivity analysis) are reported, visualised, and discussed.

With the lesson learnt in the fifth chapter, in *Towards the New Vernacular*, an optimisation study of Abdullah's building is conducted. Different strategies, systems, and relative options to increase comfort and decrease energy demand are explored. In addition, some of the well-performing options are further analysed, and through a cost-benefit and a future climate scenario analysis, the consequences of their implementation are discussed. In this analytical part, several sensitivity studies are carried out to find which systems and strategies might affect the end user's comfort of the informal building. Furthermore, by digitally re-locating Abdullah's building into different urban scenarios, the elements that influence the building performance are further analysed with the help of parametric analysis. This last point leads us to a series of recommendations that might be useful when designing a new building within this context or when retrofitting an existing one. Furthermore, limitations and outlook for further research is given.

A general summary of learnings is made in the closing remarks, and an answer to the research question is given. A reflection about the research process and its outcomes is carried out, and the connection to the overarching topics of adaptation and mitigation in the Egyptian context is made.

1.5. Related Studies Conducted by the Author

Since this research has started, to delve into and explore the research fields, three scientific papers (authorised or co-authorised) by the author – and supervised by Prof. Dietrich - have been presented at international conferences.

The first paper is titled *Passive Adaptive Strategies and Indicators for the Optimisation of Comfort and Energy Demand in Buildings in Hot Climates* and was presented at the *Cities and Climate Conference 2017 (Potsdam)*. The goal of this paper was 1) to test the methodology chosen for this research, 2) to find out to which extends different passive optimisation strategies increase thermal and energy performance of a room, 3) to find a way to compare different digital models. On that basis, a new indicator for assessing the passive optimisation of the building was developed. The results show that different optimisation strategies are possible by using this methodology, and many of them have a lot in common with approaches used in vernacular architecture (Dietrich & Vignola, 2017).

The second paper, *Optimised External and Internal Constructions in Buildings in Hot and Dry Climates to Support Thermal Comfort Without Air Conditioning*, was presented at the *Sustainable Design of the Built Environment SDBE 2018 (London)*. Using the indicator developed in the first paper and testing the same methodology, we delved into details related to constructions and materials. The results obtained by simulations and looking at correlations with different physical quantities gave suggestions about what materials and building construction perform better than others and why (Dietrich & Vignola, 2018a).

The third paper, published in 2019, is titled *Passive Strategies for Buildings in Hot and Dry Climates: Optimisation of Informal Apartment Blocks in Cairo* and was presented at the *International Sustainable Built Environment Conference SBE19 (Cardiff)*. Using Primero-Comfort software, existing informal and vernacular Cairene buildings have been modelled, and thermal comfort and energy performance simulated and compared. The performance of informal buildings has been optimised and improved by using passive strategies. As a result of the study, practical recommendations for optimising informal buildings were given (Vignola, Kiracofe, & Dietrich, 2019).

1.6. Motivation, Barriers and Support

The motivation for delving into this research (see figure 1.1) finds its basis in a personal process started about a decade ago while studying local architecture in Switzerland and India. It has endowed the author with a deep knowledge of resource-efficiency buildings and the use of empathy to understand what results might be more beneficial for their end-users. This work would have never been possible without the active help and support of other researchers, as well as academic and funding institutions.

The journey to Cairo started thanks to a collaboration between the HafenCity University Hamburg (HCU, department of Resource Efficiency in Architecture and Planning) and the Cairo University (C.U., department of Architecture at the Faculty of Engineering), funded by the German Academic Exchange Service (DAAD). The possibility to be part of this collaboration between 2016 and 2018 has allowed the author to do the preparatory work needed for this study. Site visits, exchange with local and global experts, participating in conferences, and having access to the university libraries and governmental and non-governmental institutions have helped build the fundaments of this work. The chance to lecture and coach HCU and C.U. students - that had to look at how to tackle local issues at different scales within a very challenging timeframe - has been highly motivational and inspirational. Added to that, also simply having a chat with locals, and having a look at the day-to-day life of Cairene's dwellers, feeling welcomed and enjoying the local hospitality – both in informal and formal settings – has enriched and given a sense to the whole experience.

Clearly, during this time, there have also been some barriers. The political situation of the Republic is not as stable as in other countries, which made it difficult to conduct standard research on-site, especially in informal settlements[2]. Local universities have supported the author with responsibility during the visits to Cairo. Still, it was made clear (directly and indirectly) that informal settlements should be avoided, at least for the time being. While Cairo University has been supportive of offering a safe research environment, access to experts, and publications, the author had to rely heavily on the work done before 2016 by other researchers, activists, and NGOs for working out a research framework that could result in this publication (e.g., Department of Architecture at ETH Zürich, GIZ, Cluster, Tadamun).

Lastly, while the research and work carried out at the HafenCity University has been essential to start this journey, and being supervised exceptionally, the support of funding institutions has been crucial to continue it and to bring it to an end. The German Academic Exchange Service (DAAD) has been supportive both economically (travelling for site visits and conferences) as well as for giving a chance to an American student to support the author for ten weeks in Germany (DAAD RISE). Finally, the doctoral fellowship obtained from the German National Academic Foundation (Studienstiftung des deutschen Volkes) has been essential for supporting the author both academically and financially. This has granted the opportunity to focus solely on this research for an extended period (2019-2022).

[2] See the Giulio Regeni case.

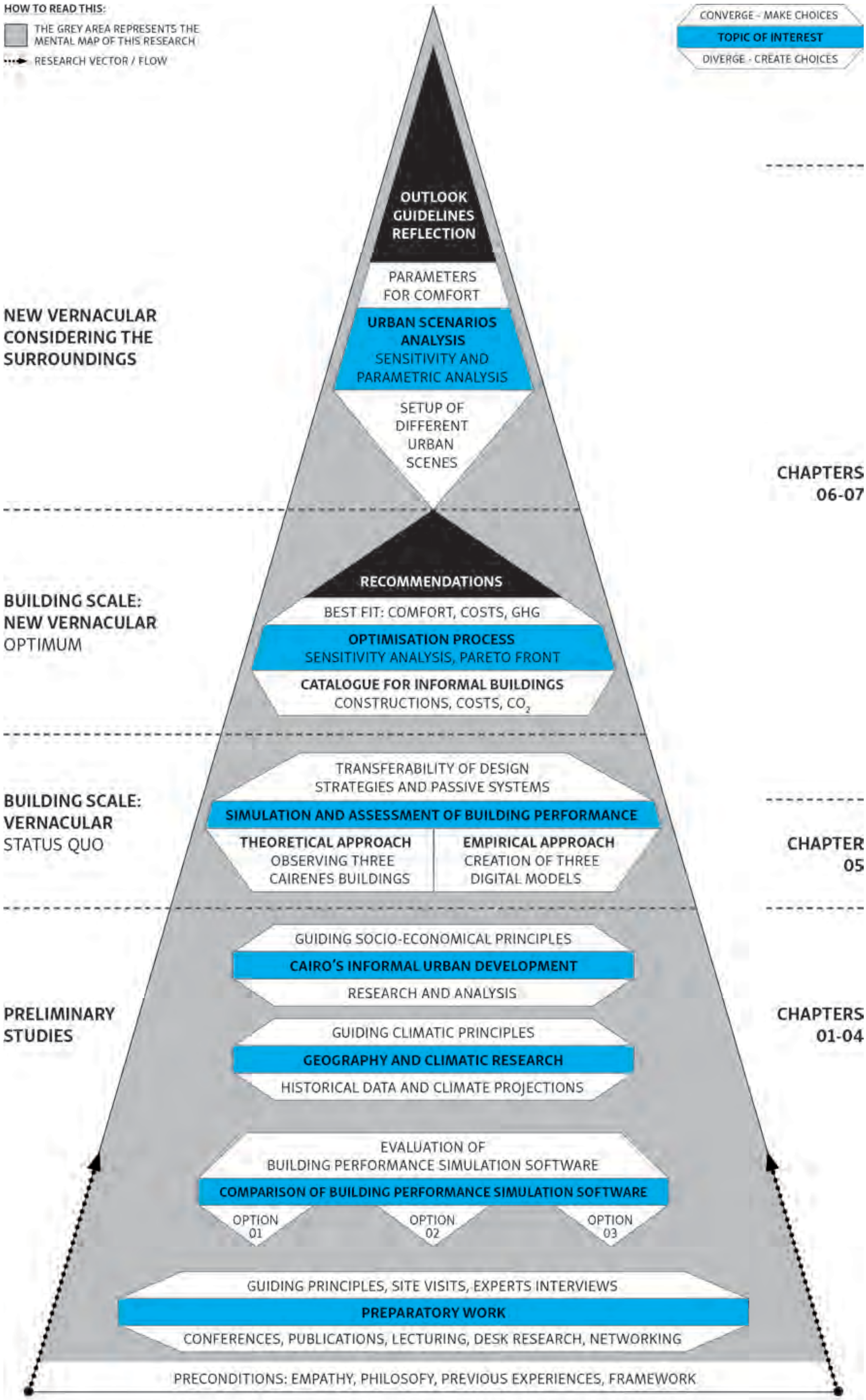

Figure 1.1 – Research Mental Map and Process. Inspired by Fleming (2021).

2. Evaluation of Building Performance Simulation Software

This research wants to build upon the lesson that can be learned from local and vernacular architecture. With analysis and simulations, we intend to find passive building optimisation strategies that help architects and planners design buildings that achieve user thermal comfort while having the lowest energy consumption possible. This chapter aims to compare different Building Performance Simulation Software (BPSS) to understand which tool might be adequate for the specific tasks involved in this study.

When looking at the number of software included in the Building Energy Software Tools website[3], more than 200 software can be found in 2020, and about 70 are listed as "Whole Building Energy Simulation". Having said that, the most natural question that comes to mind to complete this task is *how we can compare BPSS and what are the essential parameters that can help in evaluating different software in order to choose the right tool for the scope of this research?* There is a considerable number of publications and studies done in the field of building performance simulation that can help in starting to answer this question.

Some studies compare the single features of Building Performance Simulation Software. Two good examples are the ones written by Crawley, Hand, Kummert & Griffith (2008) in which 20 BPSS were compared, or the review of 10 tools done by Wen & Hiyama (2016). In these researches, aspects such as input data or capabilities to compute specific simulations were compared and evaluated.

Other publications focus on the use of software in specific design stages, such as the one published by Østergård, Jensen, & Maagaard (2016), or most recently, the study by Han, Huang, Zhang & Zhang (2018). In both cases, the authors use assessment criteria such as interoperability, simulation results, functions, core complexity, etc., to compare and evaluate the software and understand which ones are more appropriate in an early-design stage.

Other comparative studies have been done to understand if the modellers' needs are met with the use of the software they work with and to find out –most generally– what features should be optimised in BPS. Some good examples of this kind of work are the ones by Soebarto, Hopfe, Crawley & Rawal (2015) in which recommendations to BPS developers are given, the study on tools for solar design by Kanters, Horvat & Dubois (2014), and lastly, the one done by Attia, Hensen, Beltrán, & De Herde (2012), in which architects and engineers perceptions and needs are compared.

In our case, before talking about parameters and comparisons, the first choice that has been taken is related to the selection of the software to be compared. For this study, *Primero-Comfort*[4], *Trimble-Sefaira*[5] and *DesignBuilder*[6] have been chosen because they all offer educational

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[3] The website is maintained by the International Building Performance Simulation Association - United States https://www.buildingenergysoftwaretools.com/ (accessed the 18.02.2020)

[4] Primero-Comfort release R201105.27 (EnergyPlusV2-2-0)

[5] Trimble-Sefaira Online Engine and Sefaira for SketchUp plug-in© v.2.7.1 (EnergyPlus Version 8.6)

[6] DesignBuilder (EnergyPlus Version 8.9)

licences, support, and availability of online training and manuals (online or offline). This is important because the author has to self-teach the different tools. Added to that, all three software are EnergyPlus-based, which is important for a matter of comparison of results.

For comparing the software, two methods are used within this chapter. The first one includes a descriptive analysis in which *interface, design mode*, *input data*, *output data* and *functionalities* of each software are explained. A general table will help the reader to compare the different tools. The second method includes a software evaluation. This is done by adapting the contents of the research done by Attia et al. (2012). The parameters chosen by the authors of the study are divided into five categories: 1) *usability and graphical visualisation*, 2) *information management*, 3) *intelligence of knowledge base and adaptability to design process*, 4) *tool accuracy and validity*, and 5) *interoperability of building model* (Attia et al., 2012). In table 2.1, each category is explained in detail.

In the following pages, software after software, a general overview (*aim of the software*) of the different tools is given. This is followed by *a description of interfaces, basic functionalities, input data, design mode and output data.* Then, *usability and graphical visualisation*, *information management*, *intelligence of knowledge base and adaptability to design process*, and *interoperability of building model* are commented. After gaining this detailed overview and understanding features, similarities and discrepancies, and *tool accuracy and validity* of the software are compared.

Table 2.1 - Building performance simulation tool selection criteria. Adapted from Attia et al. (2012)

Usability and Information Management of Interface
The **usability** incorporates the functional operation of a tool. *Keywords*: output and input representation, navigation, control, learnability, documentation, online help, error diagnostics. The **information management** is responsible for allowing assumptions, facilitate data entry and control the input quality. Keywords: input quality control, comparative reports creation, performance benchmarking, data storage, user customization, input review & modification.
Integration of Intelligent Design Knowledge-Base
A **knowledge-based design** supports decision making and provides quantitative and qualitative advice regarding the influence of design decisions. *Keywords*: pre-set building templates & building components, heuristic/prescriptive rules, procedural methods, building codes compliance, design guidelines, case studies, design strategies. The **intelligence** entails finding quantifiable answers to design questions in order to optimise the design. Keywords: context analysis, design solutions & strategies optimisation, parametric & sensitivity analysis, 'what if' scenarios, compliance verification, life cycle and economic analysis.
Interoperability of Building Modelling
Interoperability corresponds to the ability of multidisciplinary storing and sharing of information with one virtual IBDP representation. *Keywords*: gbXML, CAD, IFC, BIM, design phases, design team, model representation.
Integration with Building Design Process
Integration with Building Design Process corresponds to the integrating of BPS tools during the whole building design delivery process. *Keywords*: multidisciplinary interfaces, design process centric, early & late design stages.
Accuracy of tools and Ability to simulate Detailed & Complex building Components
The **accuracy of tools** includes analytical verification, empirical validation and comparative testing of simulation. *Keywords*: BESTEST procedure, quality assurance, calibration, post-construction monitoring, error range The other part of this criterion deals with the ability to simulate complex building components with high model resolutions. Keywords: passive technologies, renewable energy systems, HVAC systems, energy associated emissions, green roofs, double skin facades, chilled beams, atria, concrete core conditioning etc.

2.1. Primero-Comfort

2.1.1. Aim of the Software, Target Groups, USP

Primero has been developed by the HafenCity University Hamburg[7] and includes five different modules: *Primero-Comfort*, *Primero-Light*, Primero-*Energy, Primero-Summer* and *U-Value*. What makes Primero unique in this comparison is that this is the only software in which the modelling and simulation can be done only for one room – instead of a whole building.

The general goal of *Primero-Comfort*, the module used for this research, is to design individual rooms and optimise them to achieve a higher thermal comfort and lower energy consumption. While "the program conveys the language of architects, planners along with those of engineers, energy consultants, involved in the daily planning process for the users", it "is ideally suited for use in teaching" and is primarily designed for architects and architectural students. The unique selling points described by the developers include the implementation in the early planning stage, the possibility to create variants to compare optimisation strategies, and a catalogue of about 60 typical building constructions (with the option of creating and customising new ones). Additionally, it has to be mentioned that Primero can be used free of cost (HafenCity University Hamburg, 2014).

2.1.2. Installation, Interface, and Basic Functions

Primero-Comfort can be downloaded directly from the Primero website (primerosoftware.de), where also licence keys for each Primero package module can be found. It has to be installed locally, and because the interface is Java ™ based, before being installed, both Java Runtime Environment ™ and Java3D™ have to be installed aforehand[8].

The software interface is fairly user-friendly, and the simulation process is easy to understand. The user is guided step by step in the creation of a digital room model right from the beginning. As shown in figure 2.1, the interface is divided into three main horizontal fields: the upper part gives access to all commands, variants management, technical systems, shading controls, and project data. In the central horizontal field, three distinct areas can be found: (1) a *2D plan* of the model, in which the geometry of the room and elements is visualised and controlled (in input mode); (2) a *3D visualisation tool*; (3) the *elements mask* which includes external and internal building elements, windows and doors, shading elements, internal obstruction and external elements. In the horizontal field at the bottom, four different tabs are found. *Input documentation* gives access to PDF files in which all inputs are showed. *Calculation* runs the EnergyPlus simulations writes the results on an external *.csv* file. The tab *results* runs the simulations and opens the output mask in which, e.g. *energy balance* and *comfort output* are visualised. *Error console* shows in real-time eventual mistakes appearing during the computation and simulation.

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[7] PRIMERO has been developed under the guidance of Prof. Udo Dietrich, Research Group REAP, in cooperation with ALware, the Institute for Energy and Buildings (IEG) in Nuremberg, FH Wolfenbüttel and the GWJ Technology GmbH in Braunschweig. The calculation engine used in the module *PRIMERO-light* was developed by Dr. Detlef Hennings. The software is part of a series PRIMERO of the Rud. Otto Meyer-Environmental Foundation funded research project (HafenCity University Hamburg, 2014).

[8] According to the developers, future releases of the software will be OpenJDK based (Dietrich, 2020; see also openjdk.java.net).

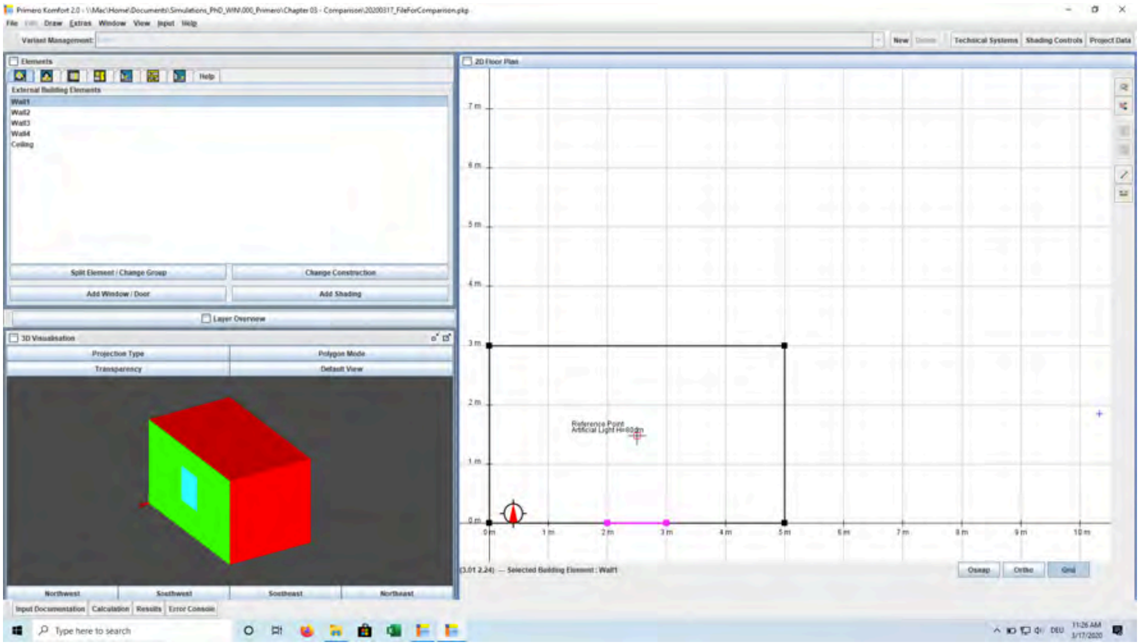


Figure 2.1 - Primero-Comfort interface.

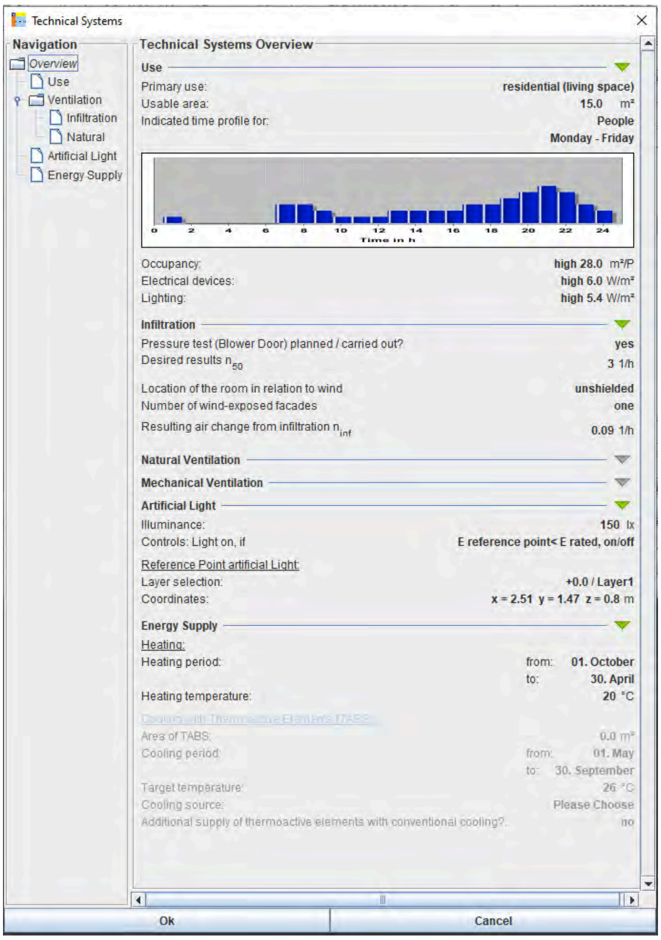


Figure 2.2 – Primero-Comfort technical systems.

Besides a short user manual, what makes Primero-Comfort easy to use and self-explanatory are *infotabs* placed strategically throughout the different input masks. By clicking these *infotabs*, *infoboxes* open and show all necessary information (including sources from norms and publications) that help fill the input. This is especially helpful when the input cannot be done by selecting items (or values) from a list but has to be digitated.

2.1.3. Input, Design Mode and Output

When opening Primero-Comfort and starting a new project, the *project data* mask and the *program flow* mask appear. The *program flow* mask is of good help in understanding the modelling and simulation process. The followings are the described steps, or phases, that are necessary from input and design to evaluation and optimisation of the digital room model:

- Phase 01: insertion of project data, orientation, and climate data
- Phase 02: geometry input
- Phase 03: elements definition
- Phase 04: input technical parameters
- Phase 05: evaluation
- Phase 06: creation of variants and optimisation

In **Phase 01**, by filling the *project data* mask, basic project information can be inserted. Additionally, climate data can be selected (if the project is based in Germany), or user-defined climate data in *.epw* format can be linked[9]. Here, the primary use of the digital room can be selected from a list of 29 uses (e.g. office, residential, commercial) and vacation times, and angle input (azimuth) can be entered. Once this is filled, the height of the room and the height of floor above ground are given.

Phase 02 consists in the creation of the digital room geometry. By using the 2D floor plan, the room can be drawn directly on the plan. Otherwise, the input can be given by using the console. While drawing directly on the plan can be unprecise, using the console requires a bit of diligence and patience because input follows an X / Y coordinates system. Nevertheless, when using the console, one can be sure that the results are precise to the millimetre. The integrated 2D design tool permits the creation of simple geometries with straight lines within any angle – curved walls cannot be drawn. Other than the room geometry also external objects can be modelled. That can be useful if a user wants to see the shading effects of nearby buildings, constructions or trees. Once the geometry is entered, it is visualised within the 3D visualisation tool.

Once the geometrical input is given, the building elements (internal and external walls, intermediate ceilings/roofs and floors) can be assigned by choosing pre-existing elements from the catalogue (**phase 03**). The building elements are self-explanatory, and values such as *insulation thickness* and *U-value* can also be inserted manually. Moreover, by clicking on the *Help* command (upper part of the screen), the documentation related to the building elements can be accessed (in German only). In the document, a sketch of the construction can be viewed, as well as all construction materials and characteristics (e.g., *thickness of materials*, *λ values*, *R values*, *U-Value of construction*, etc.). If one has already created customised building elements with the *U-Value* module (only in German), it is possible to apply them. In this phase, it is possible

[9] Climate data can be obtained e.g., from the EnergyPlus website.

to add all other elements to the building geometry. That includes windows and doors, fixed shading elements (such as overhangs), limiting interior elements, internal obstructions, and external objects. Every time a new element is added, the related input mask will open and show a series of element characteristics that can be selected and entered.

Regarding windows and doors, the mask shows a catalogue of standard glazing that can be selected. Additionally, *degree of opacity*, *U-Value of glazing*, *U-Value of frame*, and *frame to window ratio* can be entered. In the *shading in the window plane* mask, different shading possibilities are shown and can be chosen (e.g. outside rear ventilated Venetian blind, between the plane roller blind, inside film roller blind, etc.). If the options are not enough, there is the possibility to customise the shading device by entering *shading factor Fc* and *shaded g-value*. For each created window, it is also necessary to control when the shading system work (e.g. *closed when the sun is shining on the façade*, *closed during the day*, *always open*, etc.) and how the slats are positioned (*cut off*, *closed*, *fixed horizontal*). This can be done by clicking the *shading controls* tab and accessing the related mask. *Fixed shading elements* such as overhangs can be added by opening the related mask and entering depth, tilt angle, and *transmittance* of the shading element. Elements such as *internal obstructions* and *external objects* can be added as well by entering all necessary data in the related masks.

Once all building elements are assigned, it is possible to enter **Phase 04** and set up all technical systems by clicking the *technical systems* icon (see figure 2.2). In this mask *use*, *ventilation*, *artificial light*, and *energy supply* can be inserted, and a complete summary is given by clicking on the overview tab. In the mask *use*, the *profile* (people or devices) and the *use* (Monday to Friday, Saturday, Sunday) can be chosen. The occupancy profile cannot be modified. Nevertheless, it is possible to determine the *intensity of use* (low, medium, high) for *occupancy*, *electrical devices*, and *lighting*. Besides every chosen option, the values are indicated in the respective unit of measurement (m^2/P or W/m^2) as suggested by DIN 18599, Section 10.

Regarding the ventilation settings, in the *ventilation* mask, it is possible to set up *infiltration*, *natural ventilation* and *mechanical ventilation*. In the *infiltration* mask, the possible inputs regard *airtightness* (possibility to insert desired value for pressure test) and *influence of wind* (*location of the room in relation to wind* and *number of wind-exposed facades*). According to the choices, the resulting air changes from infiltration is calculated and displayed (results according to DIN EN ISO 13790). According to the experiment, simulations can be carried out by selecting natural ventilation, mechanical ventilation, or both. In the *natural ventilation* mask, two different sections are visible: *air change* (within and outside the period of use) and *ventilation strategies* (within and outside the period of use). In the section *air change,* it is possible to select how air change works by opting for the checkbox options – both within and outside the period of use: *windows with operable casements*, *cross ventilation possible*, *ventilation with height difference >4 meters possible*. Minimum and maximum air changes are then calculated and displayed according to the chosen options. In the *ventilation strategy* section, it is possible to apply minimum and maximum air changes according to the outdoor temperatures within and outside the period of use. The *mechanical ventilation* mask is built similarly to the *natural ventilation* mask. In the *air change* section, it is possible to choose when the mechanical ventilation is used (within and/or outside the period of use), but here air-change rates are entered manually. In this section, it is also possible to mention if a ground-coupled heat exchanger exists, and related information can be entered (damp or dry, and at what outside temperature the exchanger will be active).

The reference point can be set in the artificial light mask, and the rule "Light on, if …" can be chosen and entered. In the *energy supply* mask, both *heating* and *cooling periods* can be entered, as well as *heating temperature*, *target temperature* (cooling), and *cooling source*. To note is that the cooling function works only coupled with thermoactive elements. (It can be done by choosing thermoactive materials when defining construction elements.)

Once everything is set, it is possible to enter **phase 05** by clicking the *simulation* tab. Also depending on the complexity of the model, after a computation time below 10-15 seconds, the *evaluation* mask pops up. Here it is possible to get an overview of the different simulation results by looking at the following output masks:

- yearly temperatures (outside, operative, air, surface)
- heat flows (solar radiations, light, people, equipment, heating, infiltration and mechanical ventilation, conventional cooling and thermoactive elements)
- energy balance (heat flows, ventilation, cooling, air exchange rate system temperature controls on/off)
- DIN 4108 (histogram including the sum of temperatures in one year)
- EN 15251 (scatterplot with comfort zones and evaluation of categories of comfort)
- ISSO 74 (scatterplot with comfort zones and evaluation of categories of comfort)

For most users, assessing the digital model with these outputs and masks (that can also be saved as a *.pdf* file) might be enough. Nevertheless, some users might need to get into depth and access the raw data with hourly results for a full simulated year. In the *transfer* folder of the software, a *.idf* file (that can be used with EnergyPlus) and the file *sommer.csv* can be found. In *sommer.csv,* the following data is available for further use: date and time, outdoor dry bulb temperature, diffuse solar temperature, direct solar temperature, solar azimuth angle, solar altitude angle, exterior horizontal illuminance, exterior horizontal beam illuminance, people heat gains, lights heat gains, electric equipment total heat gains, transmitted solar, illumination at reference point, mean radiant temperature, mean air temperature, operative temperature, infiltration sensible heat loss, infiltration sensible heat gain, infiltration volume, infiltration air change, purchased air heating rate, purchased air total cooling rate.

Once the digital model has been evaluated for the first time, it is possible to enter **phase 06** by creating variants optimising their *technical parameters* and *element definitions*. The *variant manager* in the upper part of the interface is very straightforward, and the variant in which the optimisation is happening is always visible. Once new variants are built, by clicking again on the *simulation* tab, the results output from each variant is visible and easily comparable. It goes without saying that it is possible to get the *summer.csv* file with the raw data for each built variant.

2.1.4. Primero-Comfort – a First Evaluation

2.1.4.1. Usability and Graphical Visualisation

Thanks to a user-friendly interface and a straight-on process information mask appearing when a new project starts, Primero-Comfort gives the user the feeling to be in a "safe environment" in which everything is hands-on and under control. The navigation is straightforward, and the user can find the commands, input and outputs, within one or two mouse clicks. Generally speaking, the representation of input data of the results (both the data and the 3D visualisation) are very clear and easy to understand. Help masks are available whenever an input is entered. These factors explain why the software is easy to learn. The learning curve is short even for users that do not have experience with performance simulation or are fledgling with building physics.

On the other hand, the installation can be annoying, and reading the short installation manual before starting with it, is a must for most new users. Some minor bugs are known to the developers and are very well communicated in the user manual (see also Dietrich & Vignola, 2018b). The fact that funding is scarce makes further developments of the software difficult; nevertheless, Primero-Comfort is the only software of the ones compared in this study that is totally free of costs.

2.1.4.2. Information Management

Whenever an input is given in Primero, it is always clear what is for and what unit of measure is related to it. In case a user is unsure about the input, information boxes are there to give an idea about typical (or average) values and standards to be entered. The creation of model variants and their comparison in the output mask make the evaluation and optimisation of models easy. Once all inputs are entered, a *.pdf* file is created with all entered data by clicking the input documentation tab. This can be used for review and quality control or simple information storage. Writing about data storage, it is important to mention that Primero-Comfort does not work as a black box. It offers access to all data and files generated within the simulations. That means that expert users can make the best of the use out of it.

2.1.4.3. Intelligence of Knowledge Base and Adaptability to Design Process

The catalogue of materials and elements is complete, and thus, data entry is facilitated. Additionally, with the Primero module called *U-Value* (available only in, German) it is possible to create and customise building elements. This is very useful, especially for expert users and professionals who know all construction layers that need to be analysed. There is no option of automatically getting dynamic design strategies based on the design and performance of the model. Nevertheless, infoboxes and specific documentation help the user throughout the process by mentioning guidelines and optimisation strategies.

2.1.4.4. Interoperability of Building Model

Even though drawing the geometry in Primero-Comfort is an easy task, the software does not allow to import or export geometry. Nevertheless, as said previously, Primero is interesting because all outputs are usable and can be found for each variant simulated. In addition, every output computed is available as hourly results – for the whole simulated year – in a *.csv* file. How this amount of data might be used is limited only by the imagination of its user.

2.2. Trimble-Sefaira

2.2.1. Aim of the Software, Target Groups, USP

Trimble-Sefaira (called Sefaira from here on) is a Whole Building Simulation Software launched in 2009 with the aim, according to its creators, to become a game-changer in the industry by "creating a new type of web-based design tool that would allow green buildings to become the norm" (BRE Trust, 2011; Middleton, 2009). In 2016 it was acquired by Trimble Inc., joining SketchUp as a part of Trimble Buildings (Jensen, 2016).

Looking at the Sefaira website, it becomes clear that the target groups are architects, sustainability consultants and engineers. Trimble markets Sefaira with three unique selling points

(USPs). The first USP is that it is *fast and easy to use*; digital models can be prepared with Trimble-SketchUp and Autodesk Revit, the first results of simulations can be obtained in minutes, and the graphics are easy to understand. The second USP is based on *credibility*; it runs full hourly annual simulation, its engines are *EnergyPlus* (building performance simulation) and *Radiance* (analysis of lighting) and offers a wide range of controls and inputs. The last USP is that Sefaira is *collaborative*: it is possible to work on shared projects as a team, results are easy to peer-review, and the fact that simulation happens online can cross firm boundaries (Trimble Inc., 2019).

2.2.2. Installation, Interface and Basic Functions

Sefaira can be purchased as part of SketchUp Studio (sketchup.com). A professional licence can be obtained for 1199 \$, while a student licence costs 55 \$. Sefaira can also be used as a plug-in for Autodesk Revit. The analysis and comparison done in this research are made by using both the online platform and the plug-in for SketchUp. From now on, every time the Sefaira plug-in is mentioned, we refer to the Plug-In for SketchUp.

2.2.2.1. Sefaira Plug-in for SketchUp

After following the standard SketchUp procedure for installing a plug-in through the *extension manager*, the modeller will realise that the plug-in interface is reasonably user-friendly and visually appealing. The output and missing elements for simulation are easy to understand (see figure 2.3). In the upper part, one can choose the type of mask (*daylight and energy, daylight, energy*), can open the *entity palette*, and, by clicking on tab *upload,* can upload the model on the online platform. In the lower part of the interface, depending on the chosen mask, it is possible to visualise three different outputs: the first mode offers an overview of *energy analysis and daylight* together, the second mode show only the *daylight analysis* with its basic output, and the third option shows only the *energy analysis* including *energy gain and losses*, *location*, and *use*. By clicking the tab *properties,* it is also possible to input some basic values for walls insulation, g-values of windows, energy loads, etc. With a simple click on the *update analysis* tab, the simulation starts, and values are updated. Near to the *gain and losses* tab, another tab named *guidance* has been placed. By clicking on it, project-specific guidance is made, and targeted strategies for optimising the model are shown. These are strategies are based (and linked) on the *2030 Palette – a database of sustainable design, principles, strategies and tools* (see also Architecture 2030, 2020).

2.2.2.2. Sefaira Online Platform

On the first page of the online platform, it is possible to find a general summary of all projects. By entering the selected project, the main online interface is visible (see figure 2.4). It is very intuitive, and its input and output mask are clearly labelled. The upper part of the interface shows the title and project location, as well as a summary of outputs and HVAC system for each variant. All inputs, including *envelope*, *shading*, *space use*, *air-side*, *water-side*, *nat-vent*, *PV*, *zoning*, are accessible on the left side of the interface. On the right side, all the outputs are shown. That includes *peak loads*, *zone sizing*, *energy breakdown*, *free area*, *comfort*, *plant sizing*.Besides the higher number of inputs and outputs available on the online tool only, something else that is available online is the possibility of creating a *response curve* for almost every input. That means that nearly every input can be simulated “stand-alone.” The *response curve* simulation results will help the user in choosing the correct value for the specific input. Throughout the interface, beside each (input and output) title, a clickable question mark is there to give a short help.

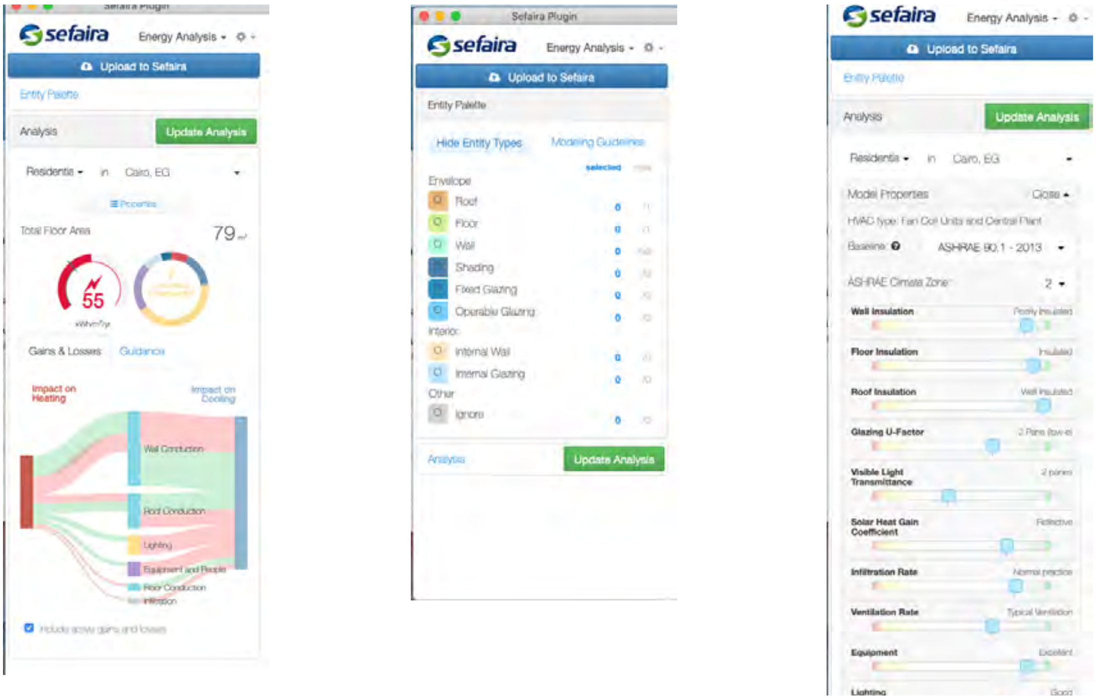


Figure 2.3 – Sefaira Plug-In interface / Energy analysis, entities, and basic inputs.

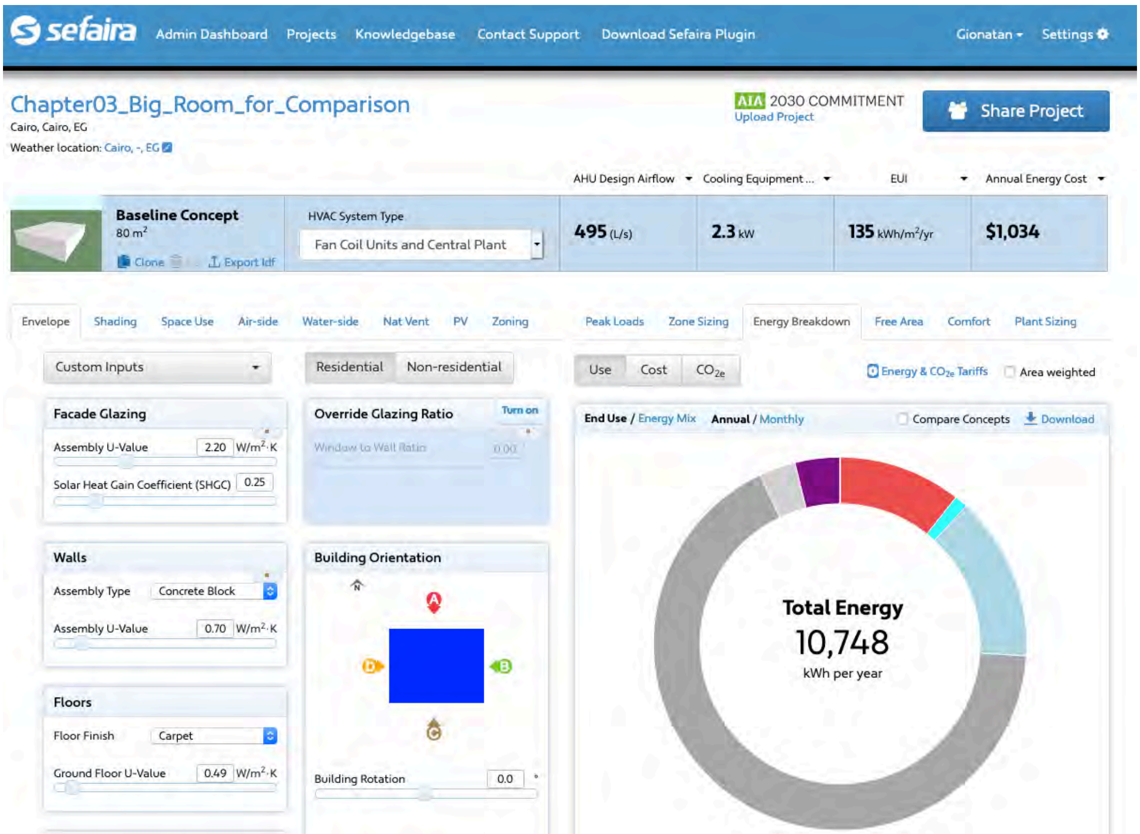


Figure 2.4 – Sefaira online platform interface.

In case in-depth information is needed, these help tabs always have links to the online Sefaira forum.

2.2.3. Input, Design Mode and Output

The steps necessary from input and design to evaluation and optimisation of the digital building model in Sefaira can be summarised with the following phases:

- Phase 01: geometry input
- Phase 02: assignation of entities
- Phase 03: element definition
- Phase 04: input technical parameters
- Phase 05: evaluation
- Phase 06: creation of variants and optimisation

Independently, if a user decides to do a basic simulation (plug-in) or go into depth with their simulation (online platform), the first two phases happen using the plug-in. The **first phase** to start using Sefaira is the creation of the 3D geometry. The simplest way is to draw the geometry directly in SketchUp. Nevertheless, it is also possible to use different software, but one has to be sure that the file can be imported into the SketchUp environment. To note is the fact that walls and floors have to be drawn as planes / thin walls. This is the only way to provide an accurate analysis (O'Connor, 2017).

Once the geometry is drawn and all building elements are drawn (including internal partitions, windows, balconies, and the other building elements), it is possible to start using the plug-in for assigning *entities*, and therefore entering **phase 02**. Tagging an entity means selecting a plane (or building element) and telling Sefaira what this element stands for. An *entity* can be a *roof*, a *floor*, *a wall*, *a shading component*, *a fixed glazing*, *an operable glazing*, *an internal wall*, *an internal glazing*. By ignoring an element, Sefaira does not include it in the analysis. (Poudel, 2020). Basically, from this point on all depends on what the user would like to achieve: for quick results and limited output, the plug-in might be the best choice; for an in-depth analysis, the model should be uploaded into the online platform.

2.2.3.1. Input and output in the Sefaira Plug-In

The first thing that must be done before starting **phases 03 and 04** is assigning use and location. The use can be chosen between six common uses (office, residential, school, healthcare, laboratory, and retail), and the location can be simply entered and selected from a list. By clicking *model proprieties,* a mask opens in which elements and basic technical settings can be set. The settings that can be customised are *wall insulation*, *floor insulation*, *roof insulation*, *glazing U-factor*, *visible light transmittance*, *solar heat gain coefficient*, *infiltration rate*, *equipment*, *lighting*. Beside the option of customising all the settings, Sefaira offers some pre-set baselines as well that include the standard settings ASHRAE 90.1, ASHRAE 189.1, Part L and Part L (2013 Notional). A total of about 30 standard settings can be downloaded from the software website (including PassivHaus, Minergie, UAE Baseline, etc.).

Once everything is set, the model is ready to be analysed and evaluated (**phase 05**), and that starts by clicking on the *update analysis* tab. If the mode chosen is *energy and daylight analysis*, all outputs generated by the plug-in are visible on one mask. For cutting down simulation time, it is also possible to choose *energy analysis* or *daylight analysis* only. The analysis output mask shows a visualisation of the following, and by clicking on every single element of the chart, the precise value of the output is given:

- energy use intensity (doughnut chart)
- energy segments (doughnut chart including heating, cooling, lighting, equipment, fans, pumps)
- annual daylighting (doughnut chart including underlit, overlit, well lit)
- gain and losses (Sankey diagram that includes impact on heating, and impact on cooling)
- daylight visualisation (3D visual representation of daylight factor, direct sunlight, specific hour sunlight, annual daylight, under and overlit areas)

Once the analysis has been run for the first time, it is possible to enter **phase 06** by changing *geometry* and/or modifying the *proprieties* to optimise further the model. Even though there is no variants manager in the plug-in, it is possible to save the current properties inputs as a *baseline*. Hence, it is possible to compare results obtained with the same geometry and different baselines. Even though the visualisations for the daylight simulation can be saved in the plug-in, all other outputs cannot be downloaded or saved. To do that, it is necessary to get into the Sefaira online platform.

2.2.3.2. Input and output in the Sefaira Online Platform

As we just saw, the plug-in is handy to get the first insight into the digital building model performance. Nevertheless, the only way to control both the inputs and the outputs of the performance analysis is to enter the Sefaira online platform. After completing phases **01** and **02** in SketchUp, the model can be uploaded on the online platform by clicking the *upload to Sefaira* tab in the upper part of the plug-in. Once the tab has been pressed, the internet browser opens, and the possibility is given to *create a new web app project*, *add the model as comparison*, and *replace an existing 3D model*. Once the first option is taken, a *new web app project* mask opens. The input can be given for *project name*, *site address*, *weather data*, *building type,* and *space use on the left side*. After having clicked on the *create new project* tab, the main interface opens. After uploading the *.epw* weather file and choosing an *HVAC system type* that suits the building needs, it is possible to insert all other relevant inputs.

Phase 03 starts by setting the envelope data in the *envelope* mask. Here it is possible to set up *façade glazing*, *walls*, *floors*, *infiltration*, *roof glazing*, *roof type* and *building orientation*. For most of the options, there is a short catalogue of options available, and then a value can be given. For example, for the *walls,* it is possible to choose the assembly type between six premade construction types (*brick*, *concrete block*, *stud*, *pre-cast concrete*, *curtain*, *exterior insulation finishing system*), and the U-value can be entered. If the values are given to elements dependent on orientation (e.g. walls), there is the option to customise the input for each plane. In case no windows have been designed in the digital model, it is also possible to turn on the *window-to-wall* ratio.

For all the mentioned parameters and the ones described later on, a *response curve* can be created. As explained in the Online Sefaira Support website: “response curves help you quickly find the optimal design choice to build strategies without manually adjusting the model. The curve is generated by running an analysis for a chosen number of steps between a desired range” (O’Connor, 2018).

Going on with the following mask, *shading* systems can be selected and implemented. Here *horizontal shading*, *vertical shading*, and *automated blinds and shades* can be set. While for the first two options only the *depth* can be entered, with the *blinds and shades* settings, some more options are given to choose from. *Shading type applied* can be *external blinds*, *internal blinds*, *external Venetians* and *internal Venetians*. The *control basis* can be *solar gain on glass*, *outdoor temperature* or *zone temperature*, and added to that, the *solar gain threshold* can be set.

By accessing the next mask named *space use*, **phase 04** can start. In this mask, the following settings can be found: *design loads* (*occupant density*, *equipment power density*, *lighting power density*), *design temperatures* (*setpoint* and *setback temperatures* for *cooling* and *heating*), *annual diversity factor* (a customisable occupancy profile), *ventilation* and *outside air settings* (*outside air rate*, *outside air rate/unit area*, *air changes per hour*), *HVAC schedule* (*operating hours* and *setback to setpoint ramp up time*), and the number of days in which *internal loads* are applied and *HVAC system* operates.

Natural ventilation settings can be controlled in the dedicated mask. Here there are options available for the coupling with the heating and cooling systems, its configuration, and the rules for being on or off. In this mask also the options for opening and glazing can be found. In the section *openness,* the *percentage of the glazed area that opens* and the *free opening area* can be entered. In the *window control options*, the rules in case the building is *unoccupied* (*all openings open or closed*) and what to do if it is *windy outside* (*all openings open or closed*) can be set. In the *zoning* mask, the *zoning strategy* can be set for each floor of the building. Here the user can decide if each room has to be considered as a zone, if the whole floor is regarded as one big zone, or if different zones are automatically generated around a central core.

There are also masks dedicated to active strategies, be it for heating, cooling or electricity generation. *Air* and *water-side* masks contain all parameters and options related to mechanical ventilation systems (heating and cooling) and hot water system. The options available are dependent on the choice of the *HVAC system type* chosen at the beginning of phase 03 and include options and inputs for *sources*, *efficiency*, *power*, *temperatures*. In the PV mask, all settings for a photovoltaic system can be found. These include PV *panel efficiency*, *panel orientation*, *panel tilt*, and *panel area*.

Once everything is set, it is possible to start **phase 05** by clicking the *update* tab on the upper side of the interface. The simulation time can range between 59 and 80 seconds (depending on if thermal comfort is on or off), and after it has been concluded, the model is ready to be analysed by looking at the outputs shown on the right side of the interface. The followings are the outputs that Sefaira offers:

- peak energy loads (cooling and heating; results given for each floor and each room; top three peak loads are visible; downloadable as .csv file)
- zone sizing (fan coil size, minimum outside air, cooling system size, heating system size; results for each floor and room are visible; downloadable as .csv file)
- energy breakdown (use; cost; CO_{2e}; end-use energy, energy mix [that includes, heating, cooling, fans, interior gains, pumps, other gas]; annual and monthly results; downloadable as .csv file)
- free area assessment criteria (tests if window openings are suitable for natural ventilation; downloadable as .csv file)

- comfort (dry bulb temperature, operative temperature, ASHRAE 55 using PMV; general results and hourly results are downloadable as .csv file)
- plant sizing (cooling, heating, air handling, heat rejection; downloadable as .csv file)

While all visualised outputs are downloadable as a *.csv* file, *energy breakdown*, *free area,* and *comfort* can also be downloaded as *.xlsx* files. To note is that only *dry bulb temperature*, *operative temperature*, and *ASHRAE 55* (under the *comfort* mask) are downloadable with hourly data for a whole simulation year. Nevertheless, a *.idf* file with all EnergyPlus data can be exported at any time.

In **phase 06,** thanks to an easy-to-use variants manager situated on top of the online interface, the *baseline model* can be *cloned*, and the variant can be optimised within all different parameters. On top of the *project* mask, a summary of the variants remains always visible. That is very helpful to get a view of four customisable outputs for each variant at a glance (there is the complete list of outputs to choose from).

2.2.4. Trimble-Sefaira – a First Evaluation

2.2.4.1. Usability and Graphical Visualisation

Both the Sefaira plugin and online platform are designed with a user-friendly interface, in which all options are available at first sight. Navigation is straightforward, and what is well done is that the user has access to a visualisation of outputs right from the beginning. Added to that, the graphs, and generally, all visual aspects of the interface, are designed following the highest standards of contemporary graphic design. And that makes the software very appealing – at least from an aesthetic point of view.

Because both SketchUp and Sefaira need to be used, a novel user has to get into Sefaira digital support to be guided both for the creation of a 3D model and then to understand how to apply the Sefaira plugin to the model. While there is quite a lot to be learned initially, as soon as the user has repeated the whole process a couple of times, everything becomes very fast.

2.2.4.2. Information Management

In Sefaira the user can always be sure about the input they are entering and modifying. Information boxes help the user with basic information about inputs and outputs – including typical values based on different building standards. If more information is required, the links given to the Sefaira digital support will answer most of the questions. The quality control of inputs can be done only within the input masks, and there is no way in which all data can be saved outside of the Sefaira environment. Creating model alternatives is possible, and the comparison is user-friendly thanks to the variant summary which is always visible in the upper part of the interface. Sefaira allows to create *.xlsx*, *.csv*, and *.idf* files with the computed data, and within some masks (*envelope* and *space-use*), settings can be saved. Nevertheless, it does not allow to save external files that include all the entered inputs, and everything is kept recorded in the cloud system or within the Sketchup file (if only the plugin is used).

2.2.4.3. Intelligence of Knowledge Base and Adaptability to Design Process

Even though for some parameters the options to choose from are limited (e.g. assembly type of building elements), the software offers quick energy analysis that supports decision making. One of the most valuable tools in this sense is the possibility to create a response curve for each design parameter (see the previous chapter). Especially when using the plugin, by clicking on the *guidance* tab, hints and tips based on the climate and the simulation results are dynamically reported following the 2030 Palette, and all in all, it is possible to say that all these features help to embrace the overall design especially during an early-design stage.

2.2.4.4. Interoperability of Building Model

The geometry used as a basis in Sefaira is managed by SketchUp, a software that offers different ways to import or export 3D drawings (e.g. *.dwg*, *.ifc*, *.stl*, *.3ds*, etc.). Therefore, even if a user works in a 3D environment different from SketchUp, they will find one way or the other to get their file to Sefaira. The output files generated by Sefaira (*.csv*, *.xlsx*, *.idf*) can be used for further analysis. It has to be said that for in-depth analysis, the only file (besides the *.idf*) that can be used for hourly analysis is the *comfort* outputs. All the others are only monthly or yearly summaries, and that could be limiting for some users.

2.3. DesignBuilder

2.3.1. Aim of the Software, Target Groups, USP

DesignBuilder is a Whole Building Simulation Software that aims to help customers maximizing occupant well-being while reducing the built environment's impact significantly (DesignBuilder, 2020a). As reported in the Best directory, it is a software that permits developing an "early-stage model all the way through to detailed design and certification without having to rip it up and start again" (Best Directory, 2020). Even though the main target groups are engineers, architects and energy assessors, considerable importance is also given to architectural and engineering students. This is proven because academic licences are very inexpensive (compared to the full licences), and access to manuals and support cover every aspect of the software's use. Some of the software's USPs are the following:

- the wide range of inputs and outputs help the user comparing the performance of alternatives,
- alternatives can be optimised following the client's objectives in all different design stages,
- with the minimum time and effort, it is possible to model complex buildings,
- high interoperability (BIM and CAD data).

Added to that, DesignBuilder is a modular software, and depending on the needs, a user can buy packages that include three or more of the following modules: 3-D modeller, visualisation, simulation, daylighting, HVAC, Cost, LEED, optimisation, scripting, CFD, certification (DesignBuilder, 2020c).

2.3.2. Installation, Interface and Basic Functions

While it is possible to buy the software with an overcharge, annual licences for DesignBuilder cost from 749 € (Energy Assessor Essential Package) to 2.799 € (Engineering Pro Package). The latter one is available with a student licence for about 70€ per year. The installation happens like any other Windows software; by clicking the setup file and following the instructions.

The software interface is user-friendly, and the screen portions are divided clearly (see figure 2.5). The central part of the screen is the one in which the user spends most of the time. Here is where all different inputs and outputs are set and shown: *geometry*, *heating design* and *cooling*

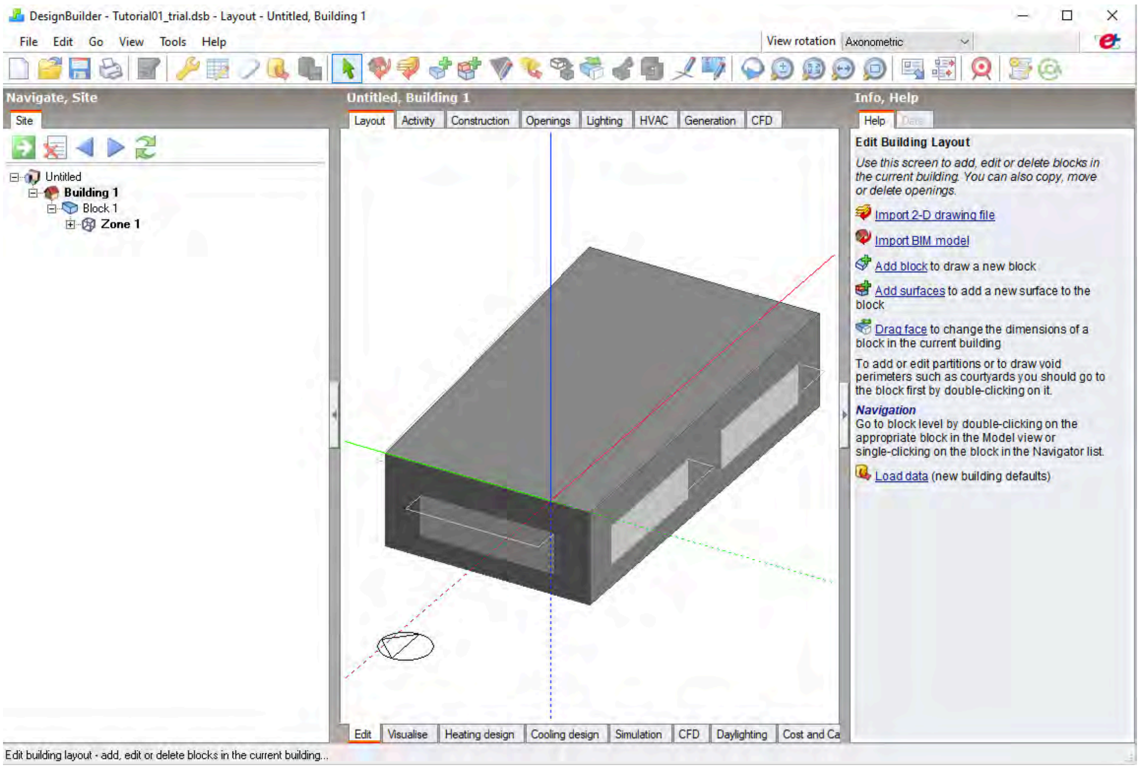


Figure 2.5 – DesignBuilder interface (in learning mode).

design, *simulation*, *CFD*, *daylighting* and *cost and carbon*. All these options are accessible in the lower part of the screen. Depending on the selected mask, the upper side of the interface will reveal new commands and inputs tabs. On the right-hand side of the screen, whether the user is working in "learning mode" or not, either a dynamic *info and help* mask or the *model data* mask is visible. The *info and help* mask gives tips and hints depending on the current tab and operation. The *navigation and site* panel are visible and accessible on the left-hand side to help the user navigate the model. Here the hierarchy of the project is shown with its different levels: site level, building level, block (or floor) level, zone level, surface level and opening level. The *data inheritance hierarchy* system permits DesignBuilder to minimise the amount of required model data entry and speed up data entry. This highest point of the hierarchy is *site*, followed by *building*, *block*, *zone*, *surface* and *opening*. The most common data is entered at the *building* level and is inherited in all the levels below.

2.3.3. Input, Design Mode and Output

The steps necessary from input and design to evaluation and optimization for the digital model in DesignBuilder can be summarized as follows:

- Phase 01: insertion of project data
- Phase 02: geometry input
- Phase 03: model data input
- Phase 04: simulation and evaluation
- Phase 05: optimisation

Phase 01 starts with the assignation of a *project name* and the *location* in the *new project* mask. After having entered that, the interface is ready with a new hierarchy of the project. At this point, it is possible to choose a template in which all necessary data is set (*climate*, *site details*, *energy codes*, *building standards*), or it is possible to create a new location by importing climate data and setting all necessary settings as needed.

The geometry can be entered by using the integrated design tool (**phase 02**). After having chosen some basic settings for the building (*activity*, *construction*, *glazing*, *HVAC and DHW*, and *lighting*) or after having accepted the default data, with the creation of simple design blocks, a whole building can be modelled within minutes. What is interesting is that, for example, when modelling a ground floor for a building, glazing is already appearing in the geometry following the rules inherited by the settings. The design tool is very comprehensive. With it, Boolean operations can be executed, as well as many of the functions that can be found in the most advanced 3D modelling software. The creation of complex models is simplified by the user-friendly interface and clear command overview (Team DesignBuilder, 2020).

Phase 03 – model data input – can start as soon as the geometry is set. The *activity* tab is where data related to the zone usage is entered and determines the majority of the building's (internal) heat gains. Specifications on different settings are made by selecting the appropriate *activity* template (there are about 450 to be chosen from). That includes values for *occupancy density*, *environmental criteria* (*heating*, *cooling* and *ventilation setpoints*, *lighting*, etc.), and *internal gains* from equipment. Schedules are set depending on the templates. All this data can be changed at the building, block, and zone level. The *construction* tab is where all non-glazed elements properties are specified. Also here, about twenty templates are ready-made. Here *walls*, *roofs*, and *floors* characteristics can be set, and if there is a need, new construction elements can be created setting the different layers of the construction, as well as U-Value and thickness. In the *openings* tab, all settings for *external windows, internal windows* and *doors* are available. *Glazing templates* can be loaded into the model to start working with set options. The windows *shading (such as blinds, louvre, etc.*) and *local shading* devices such as overhangs can also be set. The *operation* of glazing can be scheduled by choosing one of the options or can be customised (Team DesignBuilder, 2020).

By clicking on the *lighting* tab, the lighting parameters are accessible and different templates, as in the previous inputs, can be loaded or customised. *Energy consumption*, *schedule*, *task and display lighting*, and *exterior lighting* details can also be changed individually. The *lighting control* enables modelling the reduced energy consumption associated with internal heat gains based on daylight controls (Team DesignBuilder, 2020).

The HVAC tab is where the mechanical ventilation systems and some of the natural ventilation parameters are defined. The templates dictate how inputs (e.g., energy, schedules, etc.) are set. The following parameters can be enabled (or disabled) and customised under this tab: *mechanical ventilation*, *auxiliary energy*, *heating*, *cooling*, *DHW*, *natural ventilation*, *earth tube*, *air temperature distribution*, *cost*. Even though they are out of the scope of this research, other inputs are available in DesignBuilder. They are *generation* (on-site electricity generation) and computational fluid dynamics (*CFD*).

Before discussing the simulation phase, it is worth mentioning that DesignBuilder offers an extensive choice of outputs related to different software uses – and they can all be found in the lower part of the interface. *Heating design* and *cooling design* outputs are available to get an overview on *temperatures* and *heat balance* and can be helpful as the foundation for system sizing calculations. *CFD* permits the computation and visualisation of probable air velocities, pressures, and temperatures around a predefined air volume. It can be used for external and internal analysis (e.g., a wind study, occupant comfort analysis, etc.). As the name suggests, *daylighting* outputs include both visual and numerical results of daylighting analysis. *Cost and carbon* outputs allow the user to review projected construction costs and the embodied carbon in the building fabric (Team DesignBuilder, 2019b).

By clicking the *simulation* tab and entering **phase 04**, a setting window opens, and different options can be selected and given. The *simulation period* and the *output interval for reporting* can be chosen, as well as the *time steps per hour*, *temperature control*, and *solar settings*. Other than that, it is possible to select the needed data output and the kind of reports to be created for evaluation. After a simple "ok", depending on how big the data set is (output interval), a first analysis output is visible[10] in a few seconds. Here, as standard output, the graphs summarising *temperatures*, *heat gains*, and *energy consumption* related to the whole building are displayed. The followings are the outputs generated as graphs by default (*site data*):

- fuel (room electricity; lighting; heating; cooling; DHW)
- temperature (air temperature; radiant temperature; operative temperature; outside dry-bulb temperature
- heat balance (external infiltration; external ventilation; general lighting; computer + equipment; occupancy; solar gains exterior windows; zone sensible heating; zone sensible cooling)
- system loads (sensible cooling; total cooling; zone heating)
- total fresh air (mechanical ventilation + natural ventilation + infiltration)

It is also possible to visualise results by *block* (e.g., one floor) or *zone* (e.g., one room) instead of the whole building. In this case, all outputs are shown but the *fuel* ones. Added to that, the *display option* filter offers the possibility to visualise different data outputs (*site data*):

- comfort (temperatures; relative humidity; discomfort hours, e.g., adaptive ASHRAE standard 55)
- internal gains (heat balance; latent load)
- fabrics and ventilation (heat balance; total fresh air)
- fuel breakdown (room electricity; lighting; heating; cooling; DHW)
- fuel total (depending on systems used, e.g., electricity, gas)
- CO2 production
- system loads (sensible cooling; total cooling; zone heating)
- custom output (offers the possibility to display a custom set of output)

If needed, all outputs can be displayed as a grid or table. All results can be exported either in a graphical (*.emf*, *.wmf*, *.bmp*, *.jpg*, *.png*) or text/data format (*.dat*, *.csv*, *.txt*), for the selected period, and with the selected intervals (monthly, daily, hourly sub-hourly). Another remarkable feature is the *summary* tab under the *simulation* mask. The *summary* displays the simulation statistics generated by EnergyPlus. That gives the user the possibility to control all inputs and outputs related to the model (it can be saved as a *.html* file). The information that can be found in

[10] In case a complex simulation is required, it is also possible to run it by using an online simulation server such as JESS online service (http://cms.ensims.com/index.php/jess-online).

the *summary* is: *annual building utility performance*, *input verification and results*, *demand end-use components*, *component sizing*, *adaptive comfort*, *climatic data*, *envelope*, *lighting*, *equipment*, *HVAC sizing*, *system summary*, *outdoor air*, *object count*, *sensible heat gain*, *standard 62.1*.

Thanks to all this data output, the user can get a clear idea of how the model performs, and they are ready for optimisation (**phase 05**). Differently from the other analysed software, in DesignBuilder, there is no such possibility to clone the digital model and optimise different variants. Nevertheless, for optimising the performance of a building model, the software has three modes available, all of which are to be found in the *simulation* interface: *parametric analysis*, *optimisation*, *uncertainty, and sensitivity analysis*.

Parametric analysis, which is used normally during the early-design stage, is where DesignBuilder runs automatically multiple simulations creating design curves that are adjusted by two or three variables. In this way, it is possible to analyse systematically different designs and to find the ones that are optimised according to the design scope (e.g., *energy consumption* or *construction costs*). As visible in figure 2.6, the output might be displayed as a graph in which the different options and results are clearly shown (Team DesignBuilder, 2019b).

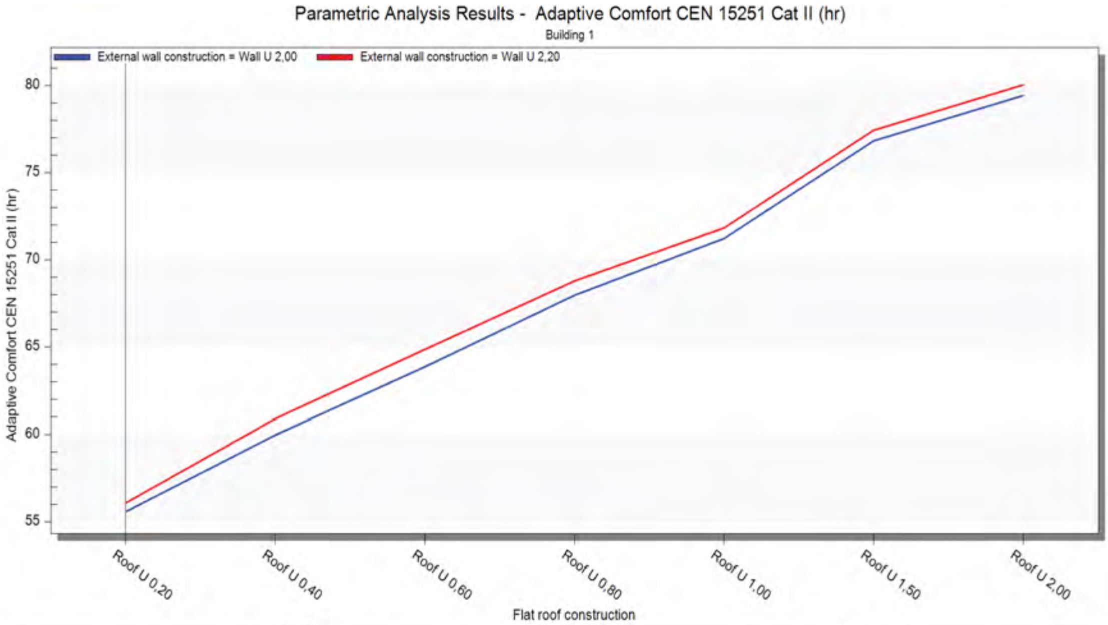
In *optimisation* mode, thanks to Genetic Algorithms [11], it is possible to widen the study by computing a multi-objective optimisation. Optimal design solutions can be calculated by including ten design parameters in combination with two objectives. That means that by using this mode, it is possible to find the best design options with, for example, both *energy consumption* and *construction costs* scopes simultaneously. As shown in figure 2.7, results are visualised both graphically (Pareto front) and as a list with all design solutions and their parameters and the relative outputs (Team DesignBuilder, 2019b).

When thinking about all different inputs – weather data, building constructions, systems information, occupant schedules, etc. – it can be said that building performance simulation is a complex process, and as in any other complex process, there are many uncertainties. Some of those uncertainties might be related to weather prediction under climate change, unpredictable building occupants' behaviours, as well as the lack of knowledge about building details, and so on. This could mine the confidence we have in the model output.

Uncertainty and sensitivity analysis make sure that the modeller can evaluate their confidence in the model. *Uncertainty analysis* helps to quantify possible input errors and as explained in the DesignBuilder Manual, "quantifies the variability of a model output due to uncertainty in the one or more input variables. *Sensitivity analysis* is the study of how the uncertainty in each simulation

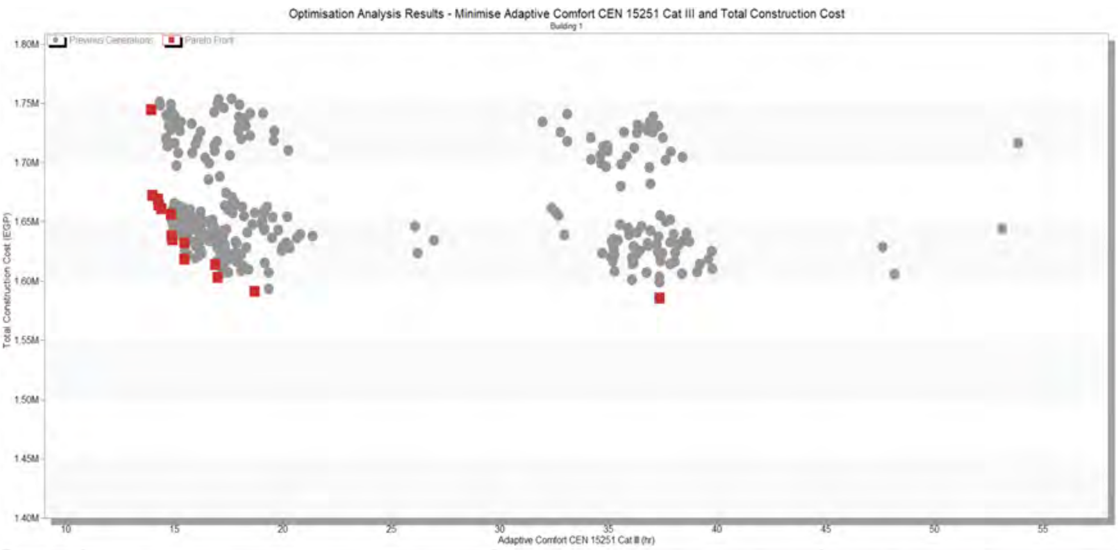
[11] While Melanie Mitchell explores genetic algorithms in her much acclaimed book (1999, The MIT Press Cambridge), here a definition given by Scott Thede (2004) in the article *An Introduction to Genetic Algorithms* (Journal of Computing Sciences in Colleges) is reported:

"A genetic algorithm is one of a class of algorithms that searches a solution space for the optimal solution to a problem. This search is done in a fashion that mimics the operation of evolution – a "population" of possible solutions is formed, and new solutions are formed by "breeding" the best solutions from the population's members to form a new generation. The population evolves for many generations; when the algorithm finishes the best solution is returned. Genetic algorithms are particularly useful for problems where it is extremely difficult or impossible to get an exact solution, or for difficult problems where an exact solution may not be required. They offer an interesting alternative to the typical algorithmic solution methods and are highly customizable".



Iteration	Adaptive Comfort CEN 15251 Cat II (hr)	Flat roof construction	External wall construction
5	80.042	Roof U 2.00	Wall U 2.20
2	77.446	Roof U 1.50	Wall U 2.20
3	71.815	Roof U 1.00	Wall U 2.20
10	68.792	Roof U 0.80	Wall U 2.20
13	64.883	Roof U 0.60	Wall U 2.20
7	60.921	Roof U 0.40	Wall U 2.20
9	56.070	Roof U 0.20	Wall U 2.20
1	79.421	Roof U 2.00	Wall U 2.00
4	76.834	Roof U 1.50	Wall U 2.00
11	71.204	Roof U 1.00	Wall U 2.00
12	67.960	Roof U 0.80	Wall U 2.00
6	63.875	Roof U 0.60	Wall U 2.00
8	59.974	Roof U 0.40	Wall U 2.00

Figure 2.6 – DesignBuilder *parametric design* output.



Status

Iteration	Generation	Status	Adaptive Comfort CEN 15251 ...	Total Construction Cost (EGP)	Embedded CO2 (kg)	External wall construction	Flat roof construction	Ground floor construction	Glazing template	Local shading type
Optimal Designs										
39	2	Optimal Designs	13.9233	1744541.646	119837.654	PhD_CH06_SA_EW_ClayBric...	PhD_CH06_SA_ROOF_EPS_...	PhD_CH06_SA_GF_Ventilate...	PhD_CH06_SA_WIN_Triple	0.5m Overhang
204	14	Optimal Designs	13.9979	1671999.862	120146.984	PhD_CH06_SA_EW_ClayBric...	PhD_CH06_SA_ROOF_EPS_...	PhD_CH06_SA_GF_Ventilate...	PhD_CH06_SA_WIN_Double	1.5m Overhang
2	0	Optimal Designs	14.2446	1668745.255	120146.984	PhD_CH06_SA_EW_ClayBric...	PhD_CH06_SA_ROOF_EPS_...	PhD_CH06_SA_GF_Ventilate...	PhD_CH06_SA_WIN_Double	1.0m Overhang
236	17	Optimal Designs	14.2606	1663816.684	106013.081	PhD_CH06_SA_EW_ClayBric...	PhD_CH06_SA_ROOF_EPS_...	PhD_CH06_SA_GF_Igloo_Mo...	PhD_CH06_SA_WIN_Double	1.5m Overhang
47	2	Optimal Designs	14.4035	1660562.076	106013.081	PhD_CH06_SA_EW_ClayBric...	PhD_CH06_SA_ROOF_EPS_...	PhD_CH06_SA_GF_Igloo_Mo...	PhD_CH06_SA_WIN_Double	1.0m Overhang
139	8	Optimal Designs	14.8458	1656200.505	116448.904	PhD_CH06_SA_EW_HollowBr...	PhD_CH06_SA_ROOF_EPS_...	PhD_CH06_SA_GF_Basis	PhD_CH06_SA_WIN_Double	1.0m Overhang
109	6	Optimal Designs	14.8708	1637843.228	97033.025	PhD_CH06_SA_EW_Stabilise...	PhD_CH06_SA_ROOF_EPS_...	PhD_CH06_SA_GF_Basis	PhD_CH06_SA_WIN_Double	1.0m Overhang
183	12	Optimal Designs	14.9047	1634586.619	97033.025	PhD_CH06_SA_EW_Stabilise...	PhD_CH06_SA_ROOF_EPS_...	PhD_CH06_SA_GF_Basis	PhD_CH06_SA_WIN_Double	0.5m Overhang
79	4	Optimal Designs	15.4681	1631965.971	119037.688	PhD_CH06_SA_EW_ClayBric...	PhD_CH06_SA_ROOF_EPS_...	PhD_CH06_SA_GF_Basis	PhD_CH06_SA_WIN_Double	No shading
164	10	Optimal Designs	15.4718	1618315.573	97033.025	PhD_CH06_SA_EW_Stabilise...	PhD_CH06_SA_ROOF_EPS_...	PhD_CH06_SA_GF_Basis	PhD_CH06_SA_WIN_Double	No shading
152	9	Optimal Designs	16.8930	1613684.831	96091.643	PhD_CH06_SA_EW_Stabilise...	PhD_CH06_SA_ROOF_EPS_50	PhD_CH06_SA_GF_Basis	PhD_CH06_SA_WIN_Single	1.5m Overhang
256	19	Optimal Designs	16.9956	1602849.072	96390.306	PhD_CH06_SA_EW_Stabilise...	PhD_CH06_SA_ROOF_EPS_...	PhD_CH06_SA_GF_Basis	PhD_CH06_SA_WIN_Single	No shading
155	[illegible]	Optimal Designs	16.6818	1590902.568	96091.643	PhD_CH06_SA_EW_Stabilise...	PhD_CH06_SA_ROOF_EPS_50	PhD_CH06_SA_GF_Basis	PhD_CH06_SA_WIN_Single	No shading
56	3	Optimal Designs	37.3387	1585168.250	99543.227	PhD_CH06_SA_EW_Stabilise...	PhD_CH06_SA_ROOF_Basis	PhD_CH06_SA_GF_Basis	PhD_CH06_SA_WIN_Single	No shading
(none)										

Figure 2.7 – DesignBuilder *optimisation* output.

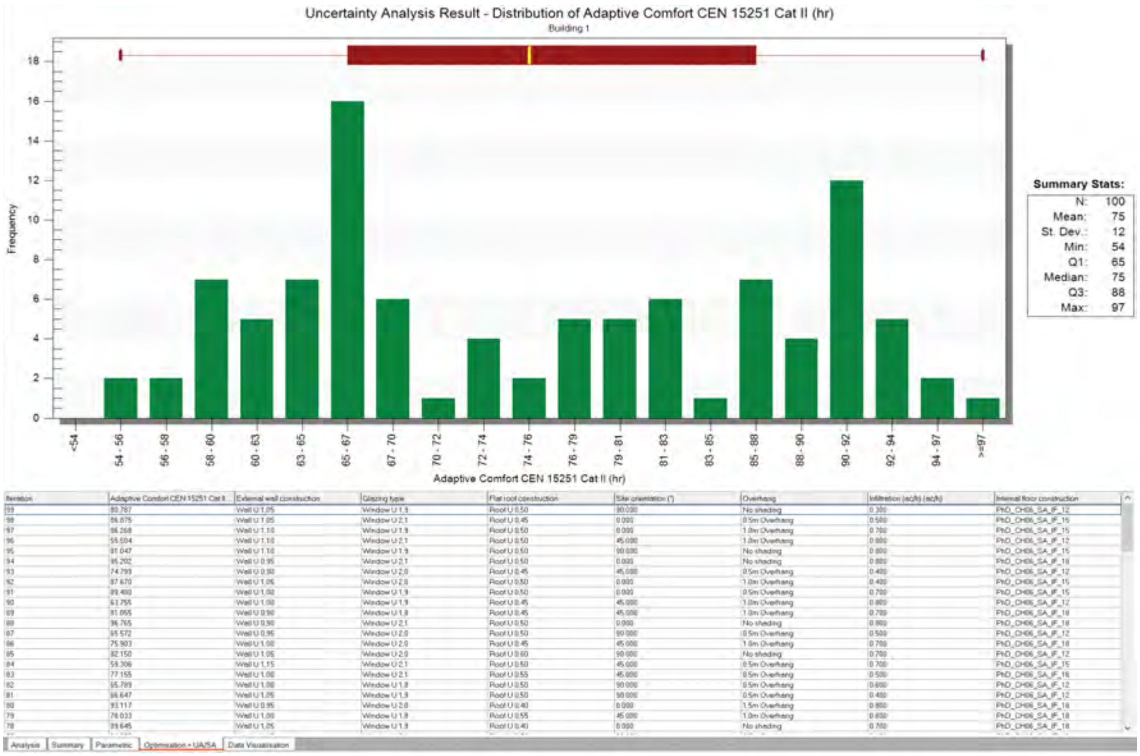


Figure 2.8 – DesignBuilder example *uncertainty analysis* result.

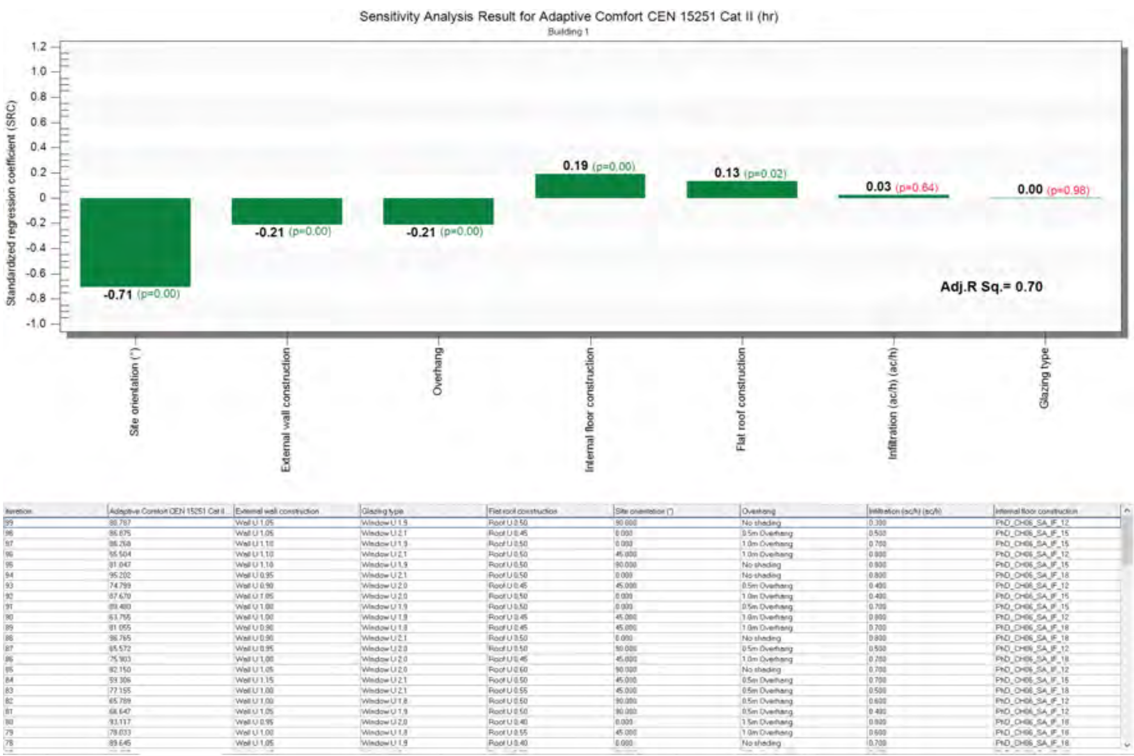


Figure 2.9 – DesignBuilder example *sensitivity analysis*.

output can be apportioned to various sources of uncertainty in its inputs" (Team DesignBuilder, 2019b, p. 1444). In other words, first, the model results uncertainty is quantified, and then, each parameter's contribution to uncertainty is evaluated using regression analysis (Team DesignBuilder, 2019b).

Sensitivity Analysis might also be relevant before starting the optimisation process for understanding which inputs have the greatest and least impact on one simulation output. With input, we mean a design variable (e.g. *wall construction U-Value*) that include a range of options (e.g. a set that contains different U-value wall constructions). The output is the target of interest (e.g. discomfort hours, embedded CO2, construction costs, etc.). Sensitivity Analysis can be run with any number of variables and outputs; by running an analysis with many variables, it is possible to discern how strong they relate to the output. Run after run, while eliminating the variables that do not show any relationship with the output, the confidence in the impact of the remaining inputs increases. (In chapters 05 and 06, this analysis is used extensively.)

2.3.4. DesignBuilder – a First Evaluation

2.3.4.1. Usability and Graphical Visualisation

DesignBuilder is designed with an interface that becomes very user-friendly after some needed time to get acquainted with. A new user might get scared from the number of tabs and inputs, but once the workflow has been tried out a couple of times, both the navigation and the workflow become clear and ordered. The input interface for the geometry is exceptionally well thought: the hierarchy system is very well structured, and the commands and drawing option tools are comprehensive. Added to that, the model can be rendered at any time for a quick check of the construction. All masks in which an input is given are well structured, and at any moment it is clear what is a setting for. Especially when a modeller is on "learning mode", whenever a tab is clicked, instructions are shown with commands and links to click on. All outputs are given in graphical form, as well as in texts and numbers. In case some spatial outputs are created, they can also be visualised in 3D.

Due to the high amount of input and output options, and also because with DesignBuilder it is possible to complete high complex building performance simulations, it takes some effort to get acquainted with the software. Nevertheless, the DesignBuilder Team offers excellent support to its customers. The user manual - with almost 2.000 pages – gives the user background information about the options and commands, as well as examples and tutorials. A comprehensive list of video tutorials that practically covers every aspect related to building modelling and simulation can be found on the DesignBuilder website.

2.3.4.2. Information Management

When looking at the data input, default values are always set to facilitate data entry and are inherited from the data hierarchy system. Once the user enters customised values, the font colour changes from blue to red; with this visual change the user always knows what comes from where. Both inputs and outputs can be quality-controlled at any time by checking, for example, the *summary* under the *simulation* tab. While the model geometry cannot be cloned, comparative and multiple alternatives can be created in different ways by *parametric analysis*, *optimisation,* or *uncertainty and sensitivity analysis*.

While DesignBuilder offers its modellers different templates filled with default data, it also enables a wide range of customisation, be it building constructions and materials, activities schedules, technical systems, etc. Even the output masks can be customised with the relevant data for the user. It goes without saying that templates can be saved, as well as DesignBuilder files.

2.3.4.3. Intelligence of Knowledge Base and Adaptability to Design Process

The simulations computed in DesignBuilder provide quick energy analysis that supports decision making within the scope or different scopes of the projects. Depending on the tools used for simulation, the software can be of help at any design stage and with varying grades of model complexity. Depending on the complexity of the model and the number of variants and parameters analysed in simulation mode, an external server might be required to cut down computing time. While a list of optimisation suggestions depending on the digital model and results is not available, sensitivity and uncertainty can be quantified in order to be evaluated.

2.3.4.4. Interoperability of Building Model

The higher interoperability of DesignBuilder is surely one of the key aspects of the software. 2D geometries as well as BIM files can be imported in DesignBuilder *(.dxf*, *.pdf*, *.bmp*, *.jpg*, *.gif*, *.tiff*, *.gbXML*), and 2D/3D/BIM models can be exported from the DesignBuilder environment *(.dxf*, *.bmp*, *.png*, *.tiff*, *.jpg*, *.gbXML*). At any time, it is possible to export EnergyPlus files *(.idf*), and the outputs generated – in whatever interval needed) can be exported as a graphic *(.png*, *.bmp*, *.jpg*), grid *(.csv*) and table *(.png*, *.bmp*, *.jpg*).

2.4. Tool Accuracy and Validity

In the previous pages, an overview of the three tools has been given, and at this point, the aim of the software, input and outputs, usability and graphical visualisation, information management, intelligence of knowledge base and adaptability to design process, as well as interoperability with other software have been analysed and discussed. In order to conclude this investigation and finally answer the question *how can we compare BPSS and what are the essential parameters that can help in evaluating different software in order to choose the right tool for the scope of this research?* one last topic needs to be analysed and discussed before evaluating the software: *tool accuracy and validity*.

As already mentioned in table 2.1, *tool accuracy and validity* include information that can be helpful to assess the reliability of computed results and the given confidence in creating a real sustainable design. While the latter point could be seen as subjective and difficult to assess, the calculated results' reliability can be validated. As explained by Judkoff & Neymark - two of the main contributors in the field of validation tests for building energy simulation - this can be done with analytical verification, empirical validation and comparative testing (1998). Analytical verification requires results obtained from a generally accepted numerical solution. The output of the software can be compared with such. By empirical validation, the software output is compared with monitored data from real structures or laboratory experiments. Comparative testing can be done by comparing a software to itself (for example, a previous version) or to software considered more physically correct and better tested (Judkoff & Neymark, 1995, 1998).

Table 2.2 – Software comparison – general information.

GENERAL INFORMATION			
	Primero	**Trimble Sefaira**	**DesignBuilder**
Aim	Room Performance Simulation	Whole Building Performance Simulation	Whole Building Performance Simulation
Target Groups	Architects and architectural students, as well as planners and energy consultants (1)	Architects, sustainability consultants, engineers, universities (2)	Engineers, architects, energy assessors, universities (3)
Unique Selling Point (USPs)	Implementation in the early planning stage; creation of variants for comparison of optimisation strategies; catalogue of building constructions; customisation of building constructions (1)	Fast & easy to use: Draw using SketchUp or Revit; Get your first results in minutes; Create easy-to-understand graphics; Credible: Runs full hourly annual simulations; Uses EnergyPlus and Radiance; Offers a wide range of inputs & controls; Collaborative: Work as a team on shared projects; Easy to peer review results; Online platform crosses firm boundaries (2)	Generate a wide range of outputs and reports to help you compare the performance of design alternatives; optimise the building at any design stage based on the client's objectives; model even complex buildings with the minimum of time and effort; import existing BIM and CAD design data to give a head start with data entry; generate impressive rendered images and movies; simplify EnergyPlus thermal simulation (3)
Pricing	Free of costs (1)	Students: 55 $ /a Studio: 1.199 $/a (2)	Students: 72 € /a Eng. Pro: 2.799 € / a (3)
Software Download	primerosoftware.de	sketchup.com	designbuilder.co.uk
Licences	primerosoftware.de	Via e-mail after registration	Via e-mail after registration
Access to online server needed during simulation?	No	No (basic simulation plug-in); Yes (in-depth simulation)	No (but possible for complex computations)
Installation / Use	Local	Local (basic simulation plug-in); Web-App (for in-depth simulation)	Local
OS platform	Windows	Windows and macOS	Windows
Pre-requirements	Java Runtime Environment™ and Java3D™	Trimble SketchUp or Autodesk Revit	None
Modules	Comfort, Light, Energy, Summer, U-Value	Energy, Daylight	3-D Modeller, Visualisation, Simulation, Daylighting, HVAC, Cost, LEED, Optimisation, Scripting, CFD
EnergyPlus Engine Version	2.2.0	8.6	8.9

(1) (HafenCity University Hamburg, 2014)

(2) (Trimble Inc., 2019)

(3) (DesignBuilder, 2020b)

Table 2.3 – Software comparison – input list.

INPUT LIST		Primero Comfort	Trimble Sefaira	DesignBuilder
Climate Data	Climate Data Catalogue	○	●	●
	User-Defined Climate Data	●	●	●
Geometry	Internal Engine	●	-	●
	Orientation Angle Input	●	●	●
	2D Viewer	●	●	●
	3D Viewer	●	●	●
	Zoning Setup	-	●	●
Building Elements	Catalogue of Walls (Nr. of Templates)	20	6	>100
	Catalogue of Roofs (Nr. of Templates)	24	4	>100
	Catalogue Floors (Nr. of Templates)	8	3	>100
	Catalogue of Windows and Doors (Nr. of Templates)	11	-	25
	Customisable U-value	●	●	●
	Customisable Walls, Roofs, Floors Construction	●	-	●
	Windows and Doors Settings	●	●	●
	Customisation of Each Window and Door	●	-	●
	Possibility to Insert Window to Wall Ratio	-	●	●
	Horizontal Shading and Settings	●	●	●
	Vertical Shading and Settings	●	●	●
	Angle of Tilt for Shading	●	○	●
	Blinds and Shades Options	●	●	●
	Customised Shading and Settings	●	○	●
	Shading Control Settings	●	●	●
Use	Primary Use (Nr. of Templates)	29	6	450
	Vacation Time Slot	●	-	●
	Daily Occupancy Profile Customisable	-	●	●
	Day Schedules (Internal Loads)	●	●	●
	HVAC System Operational Time	-	●	●
	Design Loads (Occupant, Equipment, Lighting	●	●	●
Ventilation and Infiltration	Airtightness input	●	●	●
	Air Change by Infiltration Settings	-	●	●
	Influence of Wind Settings	●	●	●
Natural Ventilation	Natural Ventilation Settings Availability	●	●	●
	Air Changes Within & Outside Period of Use Settings	●	●	●
	Minimal and Maximum Air-Changes Settings	-	○	●
	Possibility to Modify Ventilation Strategy Within Period of Use	●	-	●
	Possibility to Modify Ventilation Strategy Outside Per. of Use	●	-	●
Legend: ● = yes ; ○ = partially available ; - = not available				

Table 2.4 – Software comparison – input list continuation.

INPUT LIST (CONTINUATION)		Primero Comfort	Trimble Sefaira	DesignBuilder
Mechanical Ventilation	Choice of an HVAC System Type (Nr. of Templates)	-	15	50
	Air Changes Within & Outside Period of Use Settings	●	-	●
	Air Change Settings	●	●	●
	Possibility to Modify Ventilation Strategy Within Per. of Use	-	-	●
	Possibility to Modify Ventilation Strategy Outside Per. of Use	●	●	●
	Ground-Coupled Heat Exchanger Settings	●	-	●
Artificial Light	Control Over Artificial Light Period of Use	●	-	●
	Reference Point Input	●	-	●
Energy Supply	Heating Temperature Settings	●	●	●
	Heating Period Settings	●	-	●
	Cooling Temperature Settings	○	●	●
	Cooling Period Settings	○	-	●
	Cooling Source Settings	○	●	●
Energy Cost and CO2e Tariffs	Energy Cost Settings	-	●	●
	CO_{2e} for Energy Use Settings	-	●	●
Summary	Input Summary Availability	●	-	●
Legend: ● = yes ; ○ = partially available ; - = not available				

Table 2.5 – Software comparison – other possible inputs.

OTHER POSSIBLE INPUTS (NOT RELEVANT TO THE SCOPE OF THIS RESEARCH)	Primero Comfort	Trimble Sefaira	DesignBuilder
Air-Side Settings	-	●	●
Water-Side Settings	-	●	●
Solar Photovoltaic Settings	-	●	●
Computational Fluid Dynamics Settings	-	-	●
Legend: ● = yes ; ○ = partially available ; - = not available			

Table 2.6 – Software comparison – simulation and optimisation.

SIMULATION AND OPTIMISATION	Primero Comfort	Trimble Sefaira	DesignBuilder
Creation of Variants	●	●	●
Parametric Analysis	-	●	●
Genetic Algorithms Analysis	-	-	●
Uncertainty and sensitivity analysis	-	-	●
Legend: ● = yes ; ○ = partially available ; - = not available			

Table 2.7 – Software comparison – outputs.

OUTPUTS	Primero Comfort	Trimble Sefaira	DesignBuilder
Visual Results of Temperatures	●	-	●
Visual Results of Heat Flows	●	●	●
Visual Results of Energy Balance	●	●	●
Visual Results of Thermal Comfort	●	●	●
Free Area (is openings are big enough?)	-	●	●
Plant Sizing Results	-	●	●
Possibility to Export Results	●	-	●
Hourly Data Results in .csv format	●	○	●
Visual Results of Plant Sizing	-	●	●
Visual Results of Peak Loads	-	●	●
.idf file available	●	●	●
Costs and Carbon	-	●	●
Computational Fluid Dynamics	-	-	●
Daylighting Results	●	●	●
Legend: ● = yes ; ○ = partially available ; - = not available			

There is a variety of validation methods and standards that can be used for testing whole building performance simulation tools and programs. The most widely used are the American ANSI/ASHRAE 140, the European ISO 52017-1 or the German VDI 6020 (see for example the comparative studies of Antretter, Sauer, Schöpfer, & Holm, 2011; Kummert, Bradley, & McDowell, 2004; Strachan et al., 2006). The software analysed in this research – made an exception for Primero and including EnergyPlus[12] – have been validated by following the standard ANSI/ASHRAE 140.

And at this point, many questions might come to mind. How does the standard ANSI/ASHRAE 140 validation procedure works? What aspects have been taken into consideration for the validation of Sefaira and DesignBuilder, and with what results? And lastly, if there is a possibility of validating Primero for this research's scope, how could that be done to compare it to Sefaira and DesignBuilder for accuracy and validity? In the following pages, an answer to these questions is given.

2.4.1. ANSI/ASHRAE Standard 140-2017

The standard ANSI/ASHRAE 140 (now in version 2017) specifies how whole building simulation software and programs can be evaluated by running precise test procedures. The scope of it is to find limitations in capabilities and flows in different computed procedures of the tested software or program (ASHRAE, 2017, p. 8).

[12] See in the homepage https://energyplus.net/testing for example the reports *EnergyPlus Testing with HERS BESTEST Tests from ANSI/ASHRAE Standard 140-2011* and *Testing with Building Thermal Envelope and Fabric Load Tests from ANSI/ASHRAE Standard 140-2011* (U.S. Department of Energy, 2015a, 2015b)

Different cases that test various software capabilities are performed by following a detailed list of input specifications that includes geometry, weather data, site data, building thermal envelope and fabric load and assumptions. The outputs are compared to a range of results obtained with programs and software that are considered "robust". This comparison helps to determine if there is an agreement with the given results. In case an agreement is not met, an analysis to understand the different results can be carried out with the help of diagnostic flow charts (ASHRAE, 2017, p. 19).

The tests are divided into two main classes: *Class I* test procedures and *Class II* test procedures. The tests in *Class I* have a more simplified construction and therefore permit a better diagnostic capability. *Class II* tests have a more complex building constructions and were developed in a more realistic residential context (ASHRAE, 2017, p. 5). Because Sefaira and DesignBuilder have been tested with *Class I* procedures, from now on, we will focus on this. *Class I* test procedures are divided into *building thermal envelope and fabric load base* and *in-depth tests*.

As described in the sections 5.2.1 and 5.2.2 of the standard, *base tests* help to analyse the ability of software to model building envelope loads in the following configurations: low-mass (*cases 600, 610, 620, 630, 640, 650),* high-mass (*cases 900, 910, 920, 930, 940, 950, 960*) and free-float (*cases 600FF, 650FF, 900FF, 950FF*). While the basic geometry of all cases is consistent models vary in window orientation, shading, devices, setback thermostat, and night ventilation (ASHRAE, 2017, pp. 17, 21–30). Between other parameters, this series permits to analyse south solar transmission, solar transmittance/incidence, the effects of overhangs and fins, night setbacks, venting, thermal mass and solar interaction.

As described in section 5.2.3, in-depth tests analyse the modelling of building envelope loads for a thermostat control configuration. Cases from *195 through 320* are tested with a nondeadband ON/OFF thermostat control configuration. *Cases 395 through 440*, *800* and *810* are tested with a deadband thermostat control configuration. These tests are done to isolate the effects of specific software and program algorithms. The latter ones (*395 through 440*, *800* and *810*) have been developed to be compatible with more software and programs. Variation in the models includes: no windows, opaque windows, exterior and interior infrared emittance, infiltration, window orientation, etc. Infiltration, internal heat generation, exterior and interior solar absorbance, solid conduction, cavity albedo are some of the parameters that can be analysed with these tests (ASHRAE, 2017, pp. 17, 30–35).

Added to these procedures, under the Class I procedures, it is also possible to find ground-coupled slab-on-grade analytical verification test (5.2.4), space-cooling equipment performance tests (5.3), space-heating equipment performance tests (5.4), and air-side HVAC equipment analytical verification tests (5.5).

2.4.2. Validation Procedure for Trimble-Sefaira and DesignBuilder

As already mentioned, both Sefaira and DesignBuilder constantly validate their performance by following the ANSI/ASHRAE 140 standard.

Trimble-Sefaira describes the procedure of compliance with ANSI/ASHRAE 140 in an article on its Sefaira Online Support portal (see Bajic, 2018). In the partial report, the case models are described, and differences from the standard requirements for the tests due to input limitations are shown clearly and transparently. For example, due to the limited amount of selectable building materials and window typologies, it was only possible to find the nearest alternative to the ASHRAE requirements. Sefaira has been tested against both *basis* and *in-depth cases* (sections 5.2.1, 5.2.2, 5.2.3). In the *600* series cases (low mass), results are within the range of the other tested software for *annual heating loads* and *annual cooling loads*. Results for *annual peak heating loads* present results higher than the example range in most of the cases, and the results for *yearly peak cooling loads* are lower than the example range. The author of the article describes these results as “extremely close”. In the *900* cases (high mass), except for the *annual peak heat load* (in which results are a bit higher than the example range), all shown results are double as high as the maximum value of the example ranges. According to the author, these values are “slightly higher” due to the higher mass value of floors and exterior walls that in Sefaira cannot be modified (Bajic, 2018). After seeing these results, one could be misled and think that the software does not perform well or is unreliable. By keeping in mind that Sefaira uses EnergyPlus as a simulation engine (see note 11), and therefore should be considered reliable, what is clear from these tests, is that by using different inputs like the ones used in the test examples, one will obtain different results as expected. And this is what could give the user uncertainty and less confidence in the results. On the other hand, if it is enough for a modeller to simulate within the given limitations, results might be more than acceptable.

DesignBuilder reports the validation process as described in the Standard. The reports, which can be found on the DesignBuilder website, include a detailed description of the models, test results, and modelling notes. In the reports results from both *base* and *in-depth case*s can be found: that includes sections 5.2.1, 5.2.2, 5.2.3, 5.3.1, 5.3.2, 5.4.1, 5.4.2 and 5.5 (see DesignBuilder, 2018; Team DesignBuilder, 2019d, 2019c, 2019e, 2019a). Made exception for the sections 5.3.1, 5.3.2, 5.3.3, 5.3.4 in which certain cases have been omitted (with the explanation that it is due to EnergyPlus limitations), no cases were omitted, and none of the results have been found as *anomalous*. That means that all results have been found to be in line with the other tested software. The reports and the results of the tests clarify that DesignBuilder is a software in which all inputs can be entered as required and that the obtained results are reasonable and in line with other robust software.

2.4.3. Validation of Primero-Comfort

Primero-Software, differently than Trimble-Sefaira and DesignBuilder, has never been certified or validated by any standard. Why is that? Well, here, it is only possible to make assumptions, but the reasons might be manifold. It might be that because the software runs with the Energy-Plus engine, which has been already validated and considered “robust” (see U.S. Department of Energy, 2015b) a validation has never been seen as something necessary. Another consideration is that Primero has been developed to be used in the early-stage design and its use is (for the moment) limited to educational purposes. Commercial use has never been foreseen. Therefore, it might be that such validation would not have been necessary either. At the end of the day, for a student, it might be enough to have a basis for comparison that works and shows how the physical aspects of a building interact with each other, including the climate and the users. Or maybe the most significant barrier to validating the software is a much simpler reason; standards ANSI/ASHRAE 140, ISO 52017-1 and VDI 6020 have been created for testing whole building simulation software. Primero can simulate only one room. So, the possible limitations of testing the software due to this fact could be a significant cause against a validation.

Even though we do not know exactly why Primero has not been validated yet, nor do we want to go through a full validation process within this research, to complete the comparison of simulation software, it might make sense to see what the possible options are available to validate Primero with ANSI/ASHRAE 140.

2.4.3.1. Model Inputs Possible for Primero-Comfort and Test Selection

As already mentioned, the ASHRAE Standard includes a comprehensive and precise list of inputs and outputs for each test. In order to look at which test might be feasible with Primero, it is important to understand what the input limitations within the software are.

In table 2.8, it is possible to see a summary of section 5.2.1 of the ANSI/ASHRAE 140 input (Class I Test Procedures, Case 600: Base Case; ASHRAE, 2017, pp. 21–25), as well as the availability of input in Primero Comfort. As it is possible to see, much information can be entered directly via the user interface. That includes the use of the *weather data*, *geometry*, *infiltration rate* and *material properties*. Even though the materials specified by the Standard are not included in the standard materials catalogue, these materials can be entered as required by using the U-Wert software. For all other inputs, adjustments in Primero might be made because standard values differ from ANSI/ASHRAE requirements.

While in Primero-Comfort most of the inputs are possible through the regular use of the software – within the software interface – the developers have also thought about an advanced use of the software in which it is possible to manipulate the inputs externally, either by the use of backdoors or by manually changing the values in lists that are read by Primero when simulating.

One backdoor works by opening the *.idf* file directly in EnergyPlus (*EP-Launch*). After a check of the given inputs, it is possible to modify the needed ones. After saving the file and running the simulation within the EnergyPlus environment, it is possible to get back to Primero and see the results by clicking on "*Results*". This shows the graphical representation of the results. As seen in the related subchapter (3.1.3), it is also possible to open the *sommer.csv* file and get the hourly results in numerical format.

Another backdoor gives the advanced user the possibility to modify a *.nml* file that serves as a bridge between Primero and EnergyPlus. In simple words, the data inputs included in the *.nml* file are compiled into the EnergyPlus *.idf* file once the simulation button in Primero is clicked. By modifying the *defaults.nml* file, the user can modify, add, and remove command strings if needed. The programming language used is very similar to the one used by EnergyPlus, so for a user acquainted with it, manipulating Primero will be pretty straightforward.

The lists that can be modified externally are either *.lib* or *.txt* files in which it is possible, without any programming experience, to quickly change values that are taking into consideration when simulating. This can be done, for example, to change the standard schedules of people and equipment (files *Zeitprofil Personen.lib*, *Zeitprofil Arbeitshilfen.lib*), to change the values for the heat loads related to a specific use (*Waermelasten Nutzung.lib*), or to modify the illuminance depending on the room use (*Normbeleuchtungsstaerke.lib*).

Table 2.8 – ANSI/ASHRAE 140 - Needed input for basic cases (S. 5.2.1-5.2.2) and applicability with Primero-Comfort.

	Case 600	Case 610	Case 620	Case 630	Case 640	Case 650	Case 900	Case 910	Case 920	Case 930	Case 940	Case 950	Case 960	Case 600FF	Case 900FF	Case 650FF	Case 950FF
Weather Data and Site Data	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Building Geometry	●	●	●	●	●	●	●	●	●	●	●	●	✕	●	●	●	●
Material Properties	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Ground Coupling, and Ground Thermal Properties	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Infiltration	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Internally Generated Sensible Heat	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Opaque Surface Radiative Properties	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Exterior Combined Radiative and Convective Surface Coefficients	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Interior Combined Radiative and Convective	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Transparent Windows (Geometry and Properties)	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Interior Solar Distribution	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Mechanical Systems and Thermostat Strategies	o	o	o	o	o	o	o	o	o	o	o	o	o	-	-	o	o

Legend:
● = Applicable With Primero Interface | [o] - Applicable Through Backdoor
✕ Not Applicable | - Not Necessary
In Grey: Selected Test Cases

With this kind of manipulations, it is virtually possible to modify Primero in order to enter the data specified by the Standard. Eventually, we might be able to get similar results to the ones obtained by the EnergyPlus validation (see U.S. Department of Energy, 2015b). Nevertheless, this work aims to understand if Primero, *as it is,* is reliable. Thinking about the scope of this research – optimising a building with the use of passive strategies - only the tests that require less manipulation and are done in free float mode (no mechanical ventilation, no cooling and no heating) have been conducted (see grey areas on table 2.8).

2.4.3.2. Primero – Input for Test Cases 600FF and 900FF

For testing the cases 600FF and 900FF, as already said, the inputs related to *weather data and site data input*, *building geometry*, *material properties* and *infiltration*, were entered directly by using Primero. The weather data included in the Standard had to be converted from a *.TMY* to *.epw* file. The geometry, as well as the infiltration rate, were entered as required. For entering the materials, the use of UWert has been necessary. Whereas the materials were entered by following the Standard, the *interior surface coefficient* and the *exterior surface coefficient* are values that cannot be modified in the software. Therefore, total construction U-values vary slightly from the suggested ones (see the tables from 2.13 to 2.16).

The values that have been edited using a backdoor (file *defaults.nml*) are the *ground coupling* and its *thermal properties*, *opaque surface radiative properties*, *exterior* and *interior combined radiative and convective surface coefficients*, *transparent windows*. The *internal solar distribution* has not been modified. The strings related to *mechanical systems and thermostat strategies* have not been touched because it is possible to let the simulation run in free float mode from the interface. Something that has been of help was to look at the input code used for the

EnergyPlus evaluation[13] (see U.S. Department of Energy, 2015b). By doing this, it has been possible to be as consistent as possible (the details on the code can be found in the Appendix).

Also, some external lists have been modified in order to meet the requirements. The standard schedules of people and equipment, as well as the heat loads related to a specific use (files *Zeitprofil Personen.lib*, *Zeitprofil Arbeitshilfen.lib, Waermelasten Nutzung.lib*), have been modified to let internal heat gains generated from people remain constant at 200W throughout the year. Because in the test room no internal illumination is required, also the room illuminance file (*Normbeleuchtungsstaerke.lib)* was modified to meet the Standard.

2.4.3.3. Primero – Needed Output and Results for Test Cases 600FF and 900FF

As required by the Standard, in order to be compared with the example results, all free float cases require the following output: *annual hourly integrated maximum zone air temperature* (°C) with date and hour of occurrence, *annual hourly integrated minimum zone air temperature* (°C) with date and hour of occurrence and *annual mean zone air temperature*. By looking at the results obtained after simulating the low-mass case (600-FF), the following results can be observed (see also tables 2.9, 2.10, 2.11):

- The result is within range regarding maximum annual hourly integrated zone temperature,
- even though with only a 0,4 °C difference, the result is out of the minimum annual hourly integrated zone temperature range,
- regarding the average annual hourly integrated zone temperature, the result is out of range with a considerable +4,8 °C.

Concerning the results obtained with the high-mass case (900-FF), the following can be observed (see also tables 2.9, 2.10, 2.11):

- with 48,8 °C, the result is out of range regarding *maximum annual hourly integrated zone temperature* (+4 °C from the highest result),
- and with similar results (+5,8 °C), the result is out of the minimum annual hourly integrated zone temperature range,
- similarly to the low-mass case, the *average annual hourly integrated zone temperature* results are out of range with a considerable +5,3 °C.

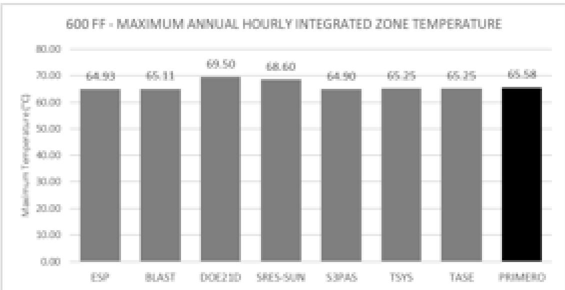
Even if two of the results are in range or near the range, most of the output values have not met the Standard, and the causes might be manifold.

To start, differences in the U-Value of both the building materials and the windows have been observed. The first point becomes clear by looking at the tables from A.1 to A.3 (Appendix), in which it is shown that the total thermal conductance (W/K) of the model is lower in Primero by about 2% in each case (104,3 W/K vs 102,9 W/K in the light-weight case and 104,2 W/K vs 102,8 W/K in the heavy-weight case).

[13] The input files can be found in the E+ help (http://energyplus.helpserve.com/Core/Default/Index) under Knowledgebase: Downloads > Testing and Validation > ANSI/ASHRAE Standard 140 > Input Files - v8.0 and higher

Table 2.9 – Maximum annual hourly integrated zone temperature - output and comparison of results.

MAXIMUM ANNUAL HOURLY INTEGRATED ZONE TEMPERATURE											
Case / Simulation Model:	**ESP**	**BLAST**	**DOE21D**	**SRES-SUN**	**S3PAS**	**TSYS**	**TASE**	**PRIMERO**	**Min**	**Max**	**Mean**
600FF - Low Mass -T (°C)	64,9	65,1	69,5	68,6	64,9	65,3	65,3	**65,6**	64,9	69,5	66,2
600FF - Low Mass (day/time)	17.10 15	16.10 15	17.10 17	16.10 15	16.10 16	17.10 16	15.10 16	**17.10 16**	-	-	-
900FF - High Mass -T (°C)	41,8	43,4	42,7	44,8	43,0	42,5	43,2	**48,8**	41,8	44,8	43,1
900FF - High Mass (day/time)	17.10 15	02.09 16	02.09 15	02.09 15	02.09 15	17.10 15	15.10 15	**02.09 15**	-	-	-



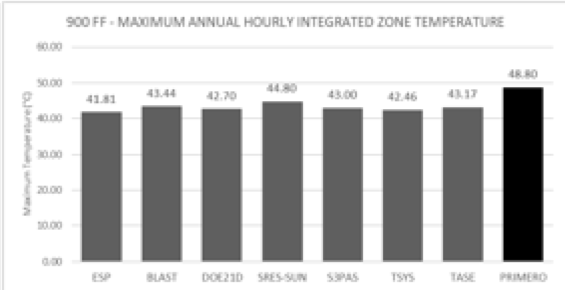


Table 2.10 – Minimum annual hourly integrated zone temperature - output and comparison of results.

MINIMUM ANNUAL HOURLY INTEGRATED ZONE TEMPERATURE											
Case / Simulation Model:	**ESP**	**BLAST**	**DOE21D**	**SRES-SUN**	**S3PAS**	**TSYS**	**TASE**	**PRIMERO**	**Min**	**Max**	**Mean**
600FF - Low Mass -T (°C)	-15,6	-17,1	-18,8	-18,0	-17,8	-17,8	-18,5	**-15,1**	-18,8	- 15,6	- 17,6
600FF - Low Mass (day/time)	04.01 7	04.01 8	04.01 8	04.01 7	04.01 8	04.01 7	08.01 9	**06.02 8**	-	-	-
900FF - High Mass -T (°C)	-1,6	-3,2	-4,3	-4,5	-4,0	-6,4	-5,6	**3,1**	-6,4	-1,6	-4,2
900FF - High Mass (day/time)	04.01 8	04.01 8	04.01 8	04.01 8	04.01 8	04.01 8	08.01 8	**04.01. 9**	-	-	-

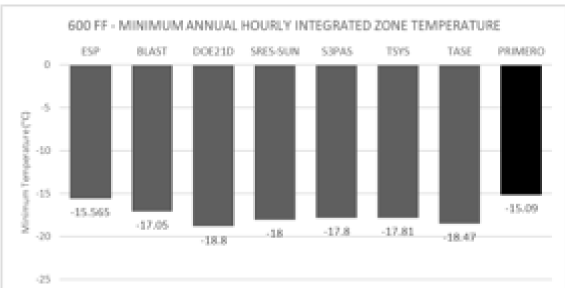
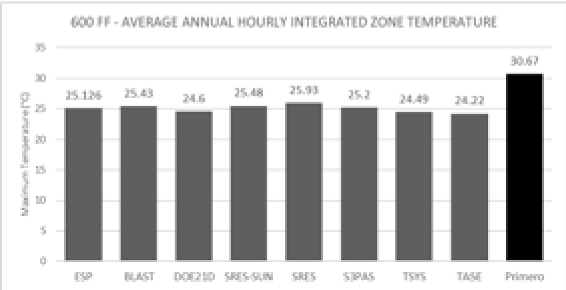
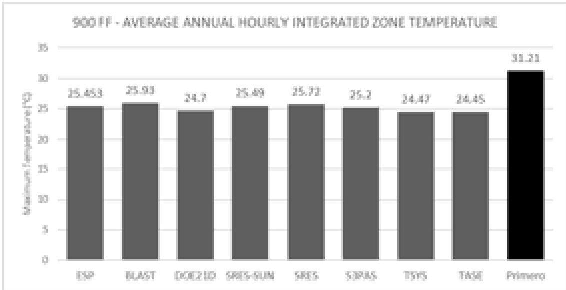


Table 2.11 – Average annual hourly integrated zone temperature - output and comparison of results.

AVERAGE ANNUAL HOURLY INTEGRATED ZONE TEMPERATURE												
Case / Simulation Model:	**ESP**	**BLAST**	**DOE21D**	**SRES-SUN**	**SRES**	**S3PAS**	**TSYS**	**TASE**	**PRIMERO**	**Min**	**Max**	**Mean**
600FF - Low Mass -T (°C)	25,1	25,4	24,6	25,5	25,9	25,2	24,5	24,2	30,7	24,2	25,9	25,1
900FF - High Mass (day/time)	25,5	25,9	24,7	25,5	25,7	25,2	24,5	24,5	31,2	24,5	25,9	25,2





The difference in values regarding walls, roof and floor was expected because the interior and exterior coefficient values cannot be changed in U-Value. Nevertheless, even though the author has made everything possible to be accurate in manipulating the *standards* file, the difference in the window's U–value cannot be explained. In the Primero model input document, the window summary reveals a 2,9 [W/(m2·K)] value where a 3 [W/(m2·K)] was expected.

Talking about manipulating the *standards* file, it is important to say that a cross-check of program strings between the Primero simulation file and the one used for validating EnergyPlus was made. The file created by EnergyPlus contains only the strings necessary to run the test. Nothing more, nothing less. Even though it has been manipulated, the file used for the simulation in Primero has been left untouched in its greater part, meaning that command strings that are not relevant for the tests have been left unchanged just as Primero would run a typical simulation. Even though the possibility is minimal, some of the manipulated strings may have been over-read by other strings or commands, and therefore the given results might contain some minor error.

The last possible cause that might be discussed is the evolution made by the simulation engine EnergyPlus. By looking at the documentation for the EnergyPlus validation, between version 2.2.0 (the one used to run Primero-Comfort), and the last version 9.3.0, a list of updates in the code, algorithms (e.g. surface convection, window convection coefficient) and their effects on the different models can be seen (U.S. Department of Energy, 2015b). Therefore, it is possible that by using different versions of the engine, different results will be given.

So, in the end, where does this partial validation brings us? Clearly, looking at the obtained results, there are still some open questions that probably only a full validation might answer.

On the one hand, even though with this partial validation the results have not been all within range, it was possible to realise how dynamically Primero can be utilised if its backdoors and external input lists are manipulated. The advanced user should be comfortable with coding, should understand exactly how both Primero and EnergyPlus work, and added to that, should have enough time at disposal: those manipulations are time-intensive.

On the other hand, as we have already seen with the validation procedure of Sefaira, entering the needed values through the standard interface would have been a limitation. Reflecting on the fact that Primero is EnergyPlus based and that the normal use might be enough for some users and uses through the standard interface, the software's robustness should not be questioned.

2.5. Evaluation of Building Performance Simulation Software - Conclusions

After having delved into different Building Performance Simulation Software, it is now possible to answer the initial question *how can we compare BPSS and what are the essential parameters that can help in evaluating different software in order to choose the right tool for the scope of this research?* and draw some conclusions about the right tools to be used in this research.

By looking into the different parameters touching upon *Usability, Graphical Visualisation* and *Information Management*, we have seen that even though the tools are very diverse, what they offer follows the highest standards (see table 2.12). Nevertheless, there is some little space for improvements left. The only aspect that might be perfectioned in Primero is the offer of direct support (be it in the form of F.A.Q. or online support). Regarding Sefaira, the fact that a user manual is missing might be replaced by the excellent online support. Added to that, focusing on *information management*, some limitations are that 1) the user cannot really have total control over the given input, 2) there is no possibility to save a “Sefaira” file and 3) the features that a user can customise are restricted. In DesignBuilder, the only point that was evaluated as *decent* is related to the *easy learnability and short learning curve*. This can be explained by looking at the level of model complexity achievable, the maximum flexibility in input options, and the different simulation modalities offered to the user. While by comparing these features with the other two software there is clearly no equal, more time is needed in order to master DesignBuilder.

The comparison of the three tools regarding *Intelligence of Knowledge Base*, *Adaptability to Design Process* and *Interoperability of Building* Model can be summarised as follows. All three software provide quick energy analysis that supports decision making. Nevertheless, DesignBuilder embraces overall design during all phases, while Primero and Sefaira might be more adequate for early-stage studies. While Primero was not developed with sensitivity and uncertainty analysis features, DesignBuilder offers a wide range of possibilities in this sense, and Sefaira allows sensitivity analysis to some extends. Suggestions to suitable climatic strategies are available on Sefaira only. Looking at the *interoperability*, DesignBuilder offers the broadest range for exchanging both digital models and simulation data. While Sefaira is limited in this last point, the exchange of digital models is supported by SketchUp – therefore, all major formats can be used for analysis. Primero cannot import digital model files but offers a complete range of options for exporting results in a graphical or numerical mode.

Tool Accuracy and Validity has been observed in much detail. While all three software can simulate models in high resolution and give confidence in creating a sustainable design, how accurate and reality-like results are, depend mainly on the modellers' use. Keeping in mind that all three tools use EnergyPlus as a simulation engine, the accuracy depends primarily on the users' expectations and on how much the user is ready to compromise between freedom and accuracy of inputs, the time needed to get results, and variety of possible outputs. On the two extremes, we find Sefaira and DesignBuilder: the first one, even though it is very limited in input and output, can simulate within minutes once a building is modelled; the second one requires more setup time but offers accurate inputs and diverse options for getting results to be compared. Between the

Table 2.12 – Software comparison and evaluation (based on Attia et al., 2012, adapted by the author [*]).

SOFTWARE COMPARISON AND EVALUATION	Primero Comfort	Trimble Sefaira	DesignBuilder
USABILITY AND GRAPHICAL VISUALISATION			
Flexible Use and Navigation	●	●	●
Easy Follow-up Structure	●	●	●
Graphical Representation of Input Data	●	●	●
Graphical Representation of Output Results	●	●	●
Graphical Representation of Results in 3D	●	●	●
Easy Learnability and Short Learning Curve Period	●	●	○
Availability of Help Masks Within the Software (*)	●	●	●
Availability of Software Manual (*)	●	-	●
On-Line FAQ / Digital Support / Direct Support (*)	○	●	●
Availability of Student Licences (*)	●	●	●
INFORMATION MANAGEMENT			
Simple Input Options for Input Review and Modification	●	●	●
Quality Control of Input	●	-	●
Creation of Comparative and Multiple Alternatives	●	●	●
Allowing Assumptions & Default Values to Facilitate Data Entry	●	●	●
Flexible Data Storage and User Customisable Features	●	○	●
INTELLIGENCE OF KNOWLEDGE BASE AND ADAPTABILITY TO DESIGN PROCESS			
Provides Quick Energy Analysis that Supports Decision Making	●	●	●
Allows Examining Sensitivity & Uncertainty of Key Design Parameters	-	○	●
Analyse Weather Data & Suggest Suitable Climatic Design Strategies	-	●	-
Embraces Overall Design During Most Design Stages	○	○	●
INTEROPERABILITY OF BUILDING MODEL			
Exchange of Model with 3D / CAD Drawing Packages / Software (*)	○	●	●
Exchange of Models or Raw Data for Further Simulations (*)	●	○	●
TOOL ACCURACY AND VALIDITY			
Confidence in Creating Real Sustainable Design	●	●	●
Accurate and Reality Like Results	○	○	●
Validated Performance Simulation Measures	-	○	●
Calibration of Model and Uncertainty	-	-	●
High Model Resolution	●	●	●
Legend: ● = very good ; ○ = decent ; - = not available			

two, even if it is a room simulation software focusing on one room only, Primero offers a wide range of customisable input, and the results can be gotten within minutes.

The comparison of different parameters evaluated in previous pages has been of help to conclude what are the tools utilised for this research. Sefaira is certainly a valid option for simulating building performance. Nevertheless, considering the aim of this study and the fact that the simulations done later are based on existing buildings (of which detailed data is available), the limitations in inputs might be a relatively big constrain for obtaining representative results.

Therefore, both Primero-Comfort and DesignBuilder will be used for the simulations. The first one is an excellent alternative to get early-phase design ideas and results, as well as to test models within a short amount of time. The second one has been evaluated as the best option for in-depth studies that require a high amount of flexibility both with input data and output options.

In any case, before getting into our case study details and look at how specific buildings perform and might be optimised by following passive strategies, in the next chapter, a brief introduction about a changing climate is given, to create a framework in which the case studies can be ordered.

3. Cairo: Geography and Climate Analysis

This chapter aims to give the reader an overview of the Egyptian Capital and to give a general description of the framework in which the experimental research is presented in the forthcoming chapters.

While this research takes Cairo as a case study, the meta-topics of the following analysis could be adapted into any kind of context – be it an urban or a rural one. Each building is embedded into a context influenced by the local geography and climate and is moulded by local socio-economic conditions. Studying how a built landscape has developed throughout the years, understanding how the geography, the climate and the socio-economic conditions of its inhabitants have been influencing this development, is a crucial point for recognizing the status quo and for critically reflect any possible vision that might be inspirational for building the future landscape.

In the following pages, after a short introduction about the Egyptian geography, we will first delve into the Egyptian climate. Historical data of the Republic is summarised, and projections for future climate are explored. With the help of room simulation, we will gain an insight into future climate trends and their possible consequences on thermal comfort. Then, we will get an overview on Cairo urban development. By focusing on the last century, we will understand how and why an impressive demographic growth took place and comprehend in which sectors that growth took place. By delving into Cairo's informal sector, we will get an overview of the living standards, as well as about the challenges and chances that informal settlements and settlers encounter. After understanding why informal buildings and dwellers an interesting and significant field of study are, we will get a first overview of passive strategies and their consequences for thermal comfort by summarising the results of previous research done with room simulations.

3.1. Geography

By looking at satellite images of Egypt (see figure 3.1), it becomes clear that Egypt offers a geographic spectacle that is quite unique. The desert plateau that covers most of the Republic's area is cut by the Nile Valley, a stretch of fertile land that measures about 1.100 km in length. This thin green line that goes from South to North, and splits the Country into Western and Eastern Desert, opens up in the Nile Delta, a triangular plateau in which the River Nile divides into two trenches and flows into the Mediterranean Sea. Greater Cairo (GC)[14], the most inhabited region in the Arab Republic and the largest African metropolitan region, is located at the Northern tip of the Nile Valley, where the Nile spreads out into the Nile Delta.

Although Egypt's area is vast (about 1 Mio. Km2), most of Egypt's population, infrastructures and activities are concentrated in the Nile Valley and its Delta, and it is not uncommon knowledge

[14] In this research, we borrow the definition of Greater Cairo used by David Sims (2012), and therefore, we use the boundaries set in the study *The strategic urban development master plan study for a sustainable development of the Greater Cairo Region in the Arab Republic of Egypt* (Nippon Koei Co. Ltd. & Katahira & Engineers International, 2008). Greater Cairo is composed by the **Greater Cairo proper** (it includes Cairo Governorate, the urban part of Giza Governorate *Giza City*, the urban part of Qalyubiya Governorate *Shubra al-Khayma*), **Peri-urban Greater Cairo** (rural districts in Giza and Qalyubiya Governorates) and **Greater Cairo´s desert**, which includes the eight desert towns found around Cairo.

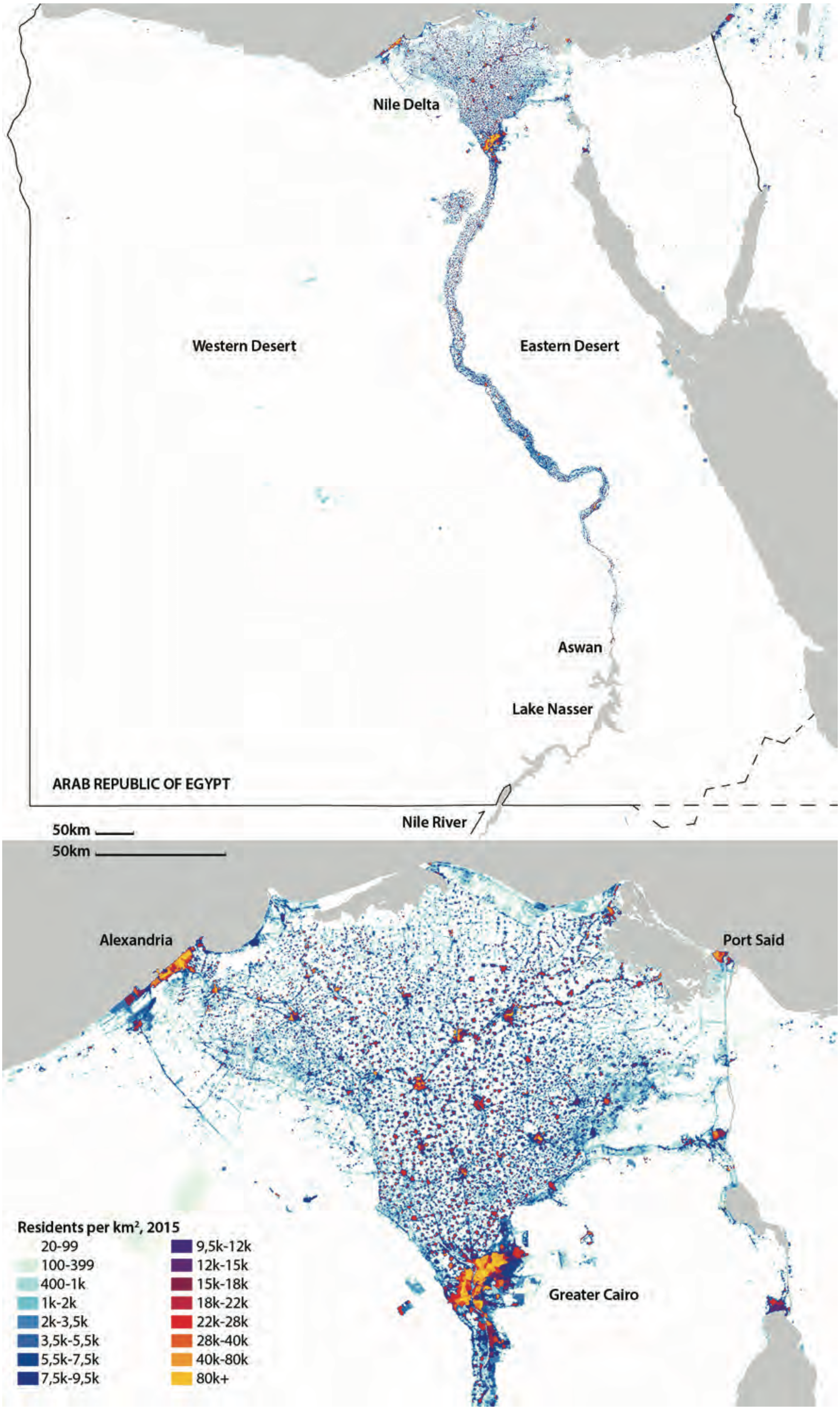

Nile Delta
Western Desert
Eastern Desert
Aswan
Lake Nasser
ARAB REPUBLIC OF EGYPT
Nile River
50km
50km
Alexandria
Port Said
Greater Cairo
Residents per km², 2015
20-99
100-399
400-1k
1k-2k
2k-3,5k
3,5k-5,5k
5,5k-7,5k
7,5k-9,5k
9,5k-12k
12k-15k
15k-18k
18k-22k
22k-28k
28k-40k
40k-80k
80k+

Figure 3.1 (Previous Page) – Population density in Egypt and the Nile delta (Adapted from EC - JRC, CIESIN, Smith, CASA, & UCL, 2016).

that about 97% of the Egyptian population lives within 4% of the Country territory (Sims, 2012; World Bank Group - Climate Change Knowledge Portal, 2020c). According to the Central Agency for Public Mobilization and Statistics (CAPMAS), in 2017, Egypt had a population of 94.798.827. According to these data, about 92 Mio. people lived in 40.000 Km^2 (CAPMAS, 2019d), which corresponds to about the area of Switzerland.

3.2. Climate: Historical Data, Trends and Projections in Egypt

Egypt is predominantly characterised by an arid to hyper-arid desert climate and is classified as *BWh* by the Köppen–Geiger climate system. In most parts of the Country mean temperature is about 25°C, and rainfall is very scarce. An exception is to be found only towards the Mediterranean coast, in which the semi-arid climate allows some rainfall outside the months between June to August, and the mean temperature is around 20°C (GERICS, 2016). According to the Climate Change Knowledge Program of the World Bank, historical data of the past 40 years shows summer temperature mean at about 30°C, while in the winter months decrease to around 15°C (see figure 3.2). Even though rainfall is very sporadic, averages are higher during the winter months, with a maximum of 4,5 mm, and around 2 mm from March to November. During spring, the Khamsin Wind (also called Khamaseen), while bringing sand and dust storms, affects the climate by dropping humidity and increasing temperatures (World Bank Group - Climate Change Knowledge Portal, 2020c).

Based on historical data available, there is a consensus about historical trends in the Egyptian climate. Even though there might be some differences in methodologies used and sources, different institutions have observed a statistically significant increase in temperatures and a decrease in precipitations, especially in the last decades. As reported by the German Climate Service Center, between 1901 and 2013, an increase in temperatures of 0,07°C/decade was observed. By looking at the last 30 years, the mean temperature increased 0,53°C/decade. A precipitation decrease was observed during the same periods: between 1901 and 2013, a decrease of -6%/30yrs was observed, while over the last 30 years, it has been -22%/30yrs (GERICS, 2016). According to the World Bank, since the 1900s, warming of about 0.03°C per century has been observed, and since 1960 a linear trend reduction in rainfall records of 2,76 mm/month (World Bank Group - Climate Change Knowledge Portal, 2020a). Another study done by El Kenawy, Lopez-Moreno, McCabe, et al. that focused on extreme daily temperatures in Egypt also reported similar conclusions. By analysing meteorological data of 40 Egyptian stations spanning the period between 1983 and 2015, an upward trend in maximum air temperature (0,6°C/decade) has been observed with a higher peak during the summer months (1,1°C/decade). Furthermore, especially during the last decade, significant increases have been observed in temperatures associated with indices such as warm days, warmest day, very warm day, and the maximum duration of warm spells (El Kenawy et al., 2019).

The trends observed in the last decades bring us to the future projections of climate. Climate projections are helpful to understand how climate might influence life in the future. Acknowledging how climate change can affect life in a country, a region, or a city is essential for developing and implementing sustainable strategies that aim to mitigate its effects while adapting to new circumstances.

The 5th Assessment Report of the Intergovernmental Panel on Climate Change (AR5 IPCC) is the most up-to-date and reliable source for scientific data and simulations of climate projections. In the report, by looking at the range of years between 2006 and 2085, different greenhouse emission scenarios are analysed: RCP 8.5 represents a high emission scenario (it is comparable to a *business as usual* situation), RCP 6.0 is a medium-high emissions scenario, RCP 4.5 is a medium-low emission scenario, and RCP 2.6 represents a low emission scenario (best-case). By looking at different 30 years periods from 2006 and 2085 and as reported by the German Climate Service Center (GERICS, 2016), the following projections can be drawn with medium confidence:

- Annual mean temperature: as shown in figure 3.2, it is very likely that temperatures will increase by +1.0 to 2.2°C in 2030, +1.3 to 3.4°C in 2050, and +1.1 to +6.1°C by 2085. It is likely that that the change will be of +1.2 to 2.0°C in 2030, from +1.6 to 2.9°C by 2050 and from +1.8 to +5.2°C by 2085. By 2085 The low scenario median is observed at +1.6°C while in the high scenario is +4.9°C.
- Annual maximum temperatures are likely to be in the range of +1.3 to +2.4°C by 2030, from +1.7 to +3.4°C by 2050 and from +2.1 to +5.7°C by 2085.
- Annual minimum temperatures are likely to be in the range from +1.1 to +1.7°C by 2030, from +1.4 to +2.6°C by 2050 and from +1.5 to +4.6°C by 2085.
- Long-lasting heatwaves duration is very likely to increase the range from +3 to +23 days by 2030; +4 to +47 days by 2050; +3 to +100 days by 2085 and likely to increase from +5 to +15 days by 2030, from +7 to +31 days by 2050 and from +9 to +77 days by 2085. By 2085 the low scenario median is observed at +6 days while in the high scenario is +69 days.
- Long-lasting cold spell duration is very likely to be in the range from -5 to -1 days by 2030; -6 to -1 days by 2050; -7 to -2 days by 2085. By 2085 the low scenario median is observed at -3 days while in the high scenario is -6 days.
- Precipitation projections show an increase in annual total precipitations by 2085 of 1% when simulating a low-scenario, while with the high-scenario a decrease of 9% can be observed.
- Heavy rainfalls events by 2085 will likely increase by 7% (median low-scenario) and 19% (median high-scenario);
- There is not a strong signal in change of annual wind speed;
- sea-level change on the Mediterranean Coast is projected to be between +0.23 and +0.29 meters (mean of low-scenario and high-scenario) by 2056 and between +0.34 and 0.58 meters by 2090 (GERICS, 2016).

These projections suggest that the trends observed during the last decades will continue in the future and even worsen. Extraordinary events such as heavy rainfall, heatwaves and maximum temperature will be more frequent and extreme. By looking at the "business as usual scenario" (RCP 8.5), it is clear that mean temperatures might rise much more than the maximum of 1.5° Celsius limit increase aimed with the Paris Agreement.

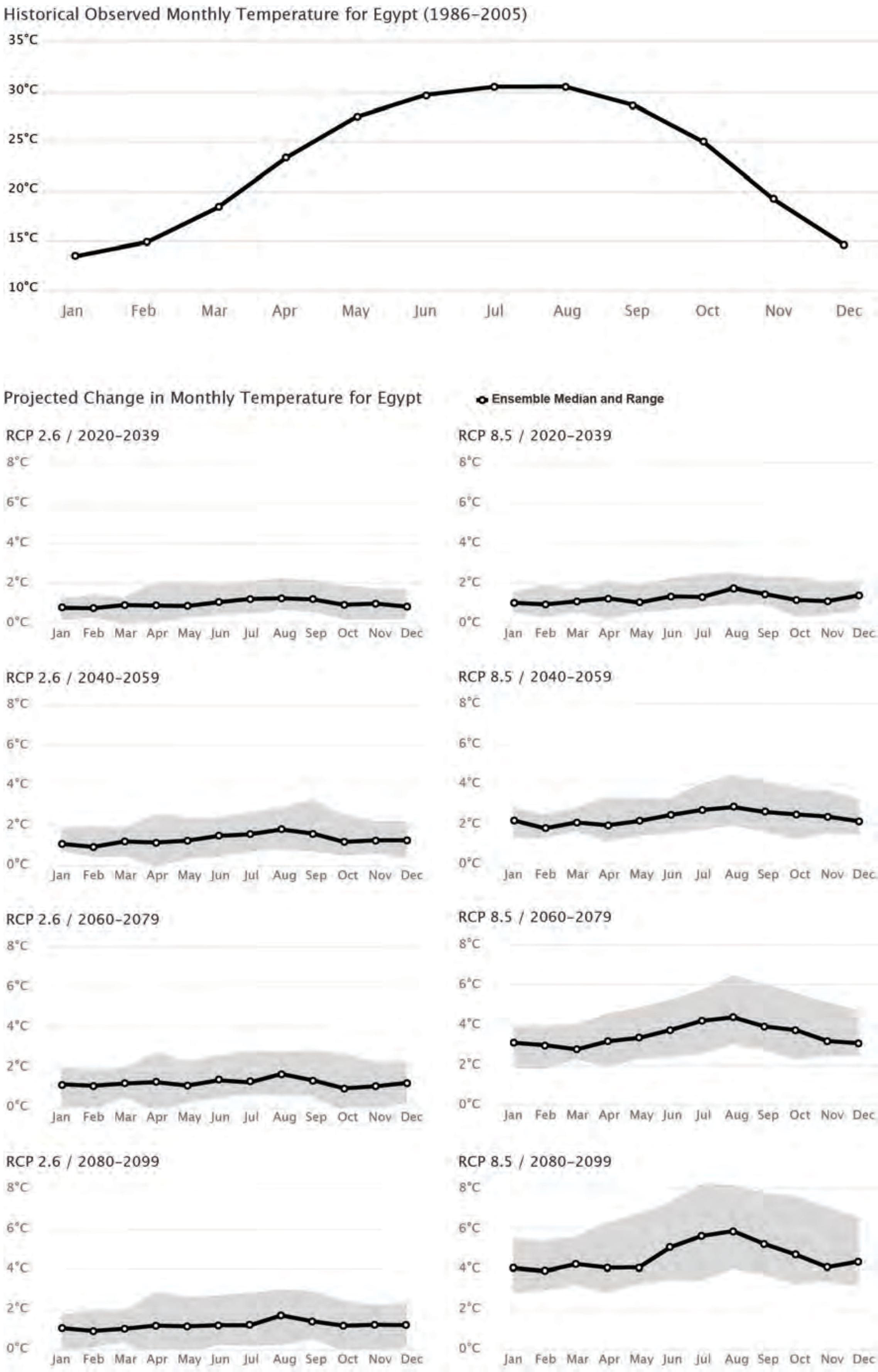


Figure 3.2 – Historical and projected change in monthly mean temperature in Egypt. Adapted from World Bank Group: Climate Change Knowledge Program (2020a, 2020b)

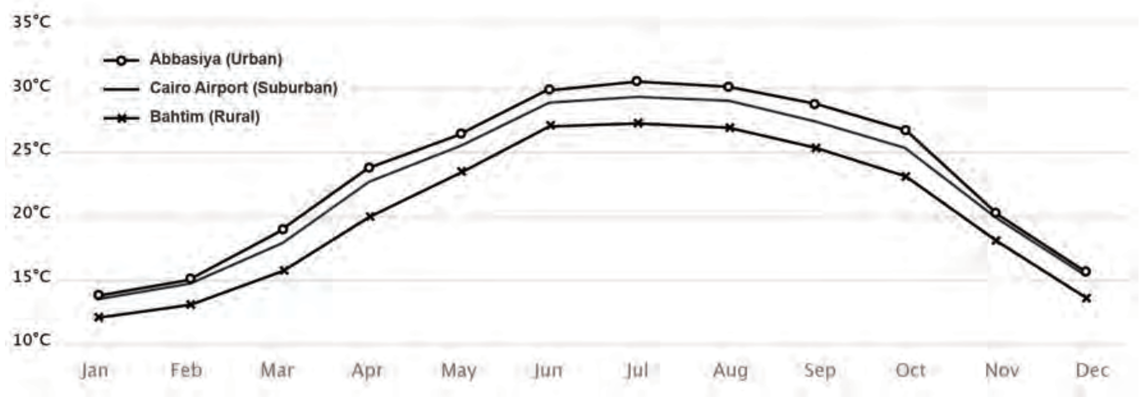


Figure 3.3 – Mean annual variation of mean temperature, T (°C) in the urban, suburban and rural areas in Greater Cairo Region (1990- 2010). Adapted from Robaa (2013)

3.3. Climate: Historical Data in the Greater Cairo Region

As seen in the previous pages, Egypt already sees the consequences of the changing climate with rising temperatures and more frequent extreme events. As observed by El Kenawy et al., this "could have profound ecological, hydrological and socio-economic impacts, especially for crop production, water resources management and energy consumption" (2019).

And how does the climate situation in the Egyptian Capital looks like? It is difficult to generalise on a city that, within its 214 km^2, includes a manifold offer of urban, rural and industrial landscapes, all of which have a different impact on the local urban climate. Robaa, in its article *Some aspects of the urban climates of Greater Cairo Region, Egypt* (2013), was able to delve into the urban climate of five Cairenes districts and investigate the climate data of 20-years measurements (1990-2010). The study pointed out the differences and impact that different levels of urbanisation and industrialisation have on parameters such as temperature (minimum, maximum, mean), wind speed, relative humidity, cloud amount and rainfall amount. The results of the study clearly show that while industrialisation processes are stronger than the effects of urbanisation on climatic elements, whenever the urbanisation degree increase, also the values related to temperatures increase while dropping in wind speed, relative humidity, cloud amount and total rainfall amounts (Robaa, 2013). In figure 3.3, the results of three districts are shown (rural, suburban, urban). It can be noted that while mean monthly temperatures are similar to the ones computed at the country scale (figure 3.2), the mean temperatures drop with the decrease of urbanisation.

By carrying out a climate analysis with the software Climate Consultant, it is possible to see what the most important constraints of the Cairene climate are, and it is possible to have a first overview on the measures that might be important when designing a new building. In the figure 3.4, some of analysis results are shown. By looking at temperatures, we might observe that while in summer colling might be necessary, in winter heating might be required. As it shown in the 3D temperature chart, 23% of hours are uncomfortable (>27°), therefore, measures to keep inside temperatures lower than outside temperature are needed. The sun shading chart shows that solar heat gains are high during summer months. Measures such a small window to wall ratio or shading elements might be required. Winds coming from the desert might be useful for natural ventilation. Nevertheless, considering that also dust is brought together with the air, measures might be needed to keep the dust out. The following are generally recommendations that might be used in this climate:

- high thermal mass and (e.g.) concrete core activation can be used to maintain temperature constant and cool down the building in summer (especially at nighttime),
- sun shading of windows (e.g., overhangs and operable sunshades) are required to control solar heat gains: In summer solar heat gains are not allowed, while in winter are welcomed,
- internal heat gains are needed during the colder months, therefore, ways to keep building envelope tight are needed,
- natural ventilation, fan forced ventilation and evaporative cooling might be required during warm hours (>27°C). Use of open plan interiors can promote ventilation. Outdoor sun shaded spaces (e.g., porch, patio, terraces) can also be effective in providing passive comfort cooling.

3.4. Climate Projection and Their Influence on Thermal Comfort in Cairene Buildings

After having seen how climate changed in the past and what might be some of the consequences of a changing climate in Egypt and the Greater Cairo Region, it becomes clear that it is very likely that in the future, Cairene's dwellers will have to deal with higher temperatures and extraordinary events. Thinking about architecture and the fact that buildings often have a longer lifespan than humans, we must consider that whatever will be built today should be adaptable and "inline" with future transformations that climate might bring. At this point, the question that arises when thinking about the focus of this research is *how do the climate projections might influence the thermal comfort of buildings in the future?* Or, in other words, if we could travel through time, how will the TO temperature of a building – and the thermal comfort of its users - change through time?

3.4.1. Projected Performance of Two Rooms in the Greater Cairo Region

To start answering this question, we are going to take inspiration from an experiment recollected by one of the most known Egyptian architects, and then we are going to add a more modern twist, experimenting with Building Performance Simulation.

In the book *Natural Energy and Vernacular Architecture* published in 1986, Hassan Fathy mentions an experiment done in the 60s on the ground of the Cairo Building Research Institute. Six small buildings were erected to evaluate thermal comfort, availability of materials and costs (p. 40). By comparing the worst and best-performing buildings, it was clear that with observations obtained the same day (same outdoor temperature), the operative temperature (T_O) of the buildings built in mud bricks was way lower than the prefabricated concrete model (pp. 76-79). We can assume that if those buildings were still accessible, and we would have the chance to take measurements today, we would observe a similar performance. Although it is not the case, if those buildings' temperatures had been monitored until our days, we could have expected to see increased operative temperatures throughout the last decades following the patterns mentioned in chapter 3.2.1 (see El Kenawy et al., 2019; GERICS, 2016; World Bank Group - Climate Change Knowledge Portal, 2020a).

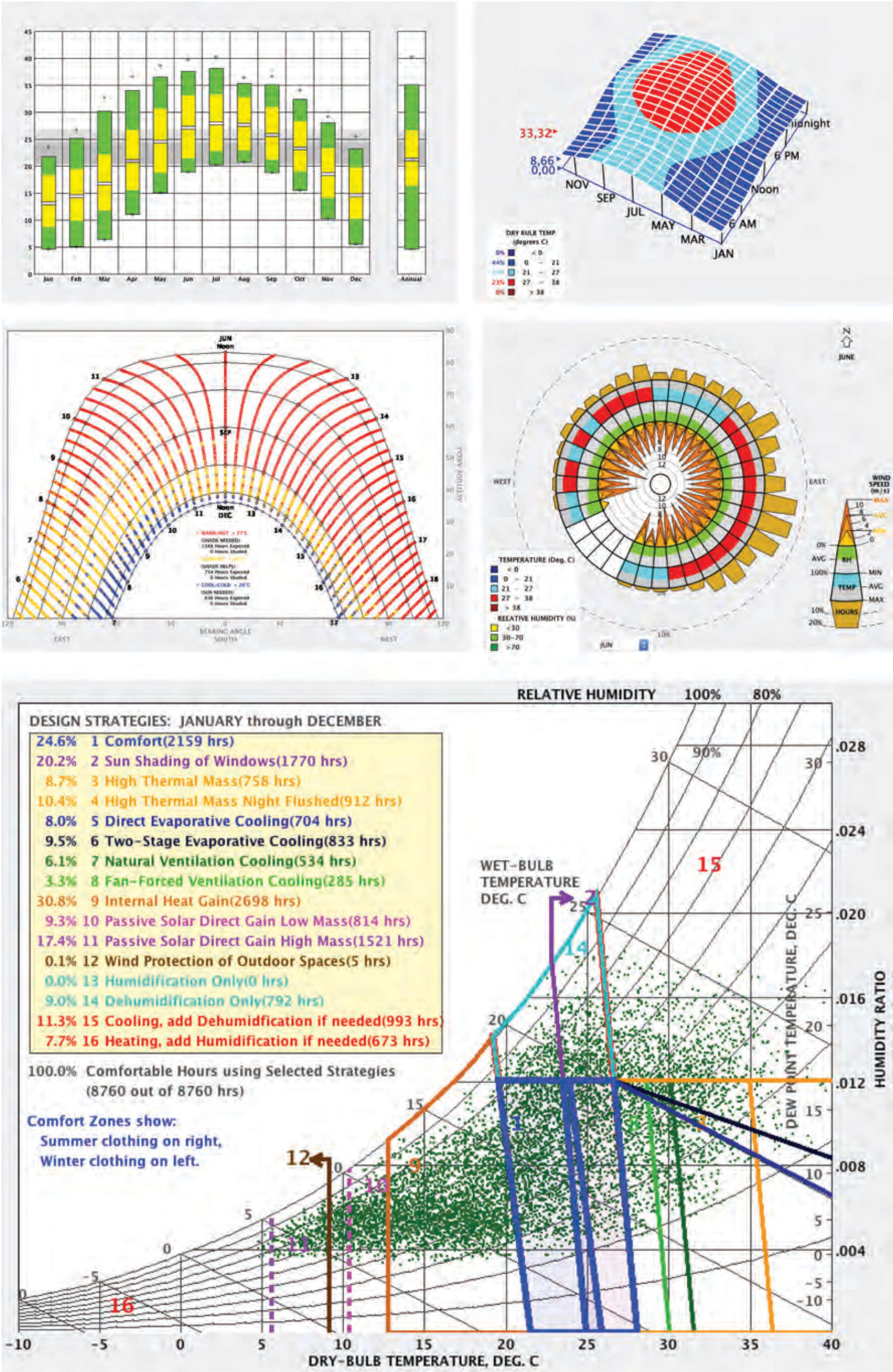
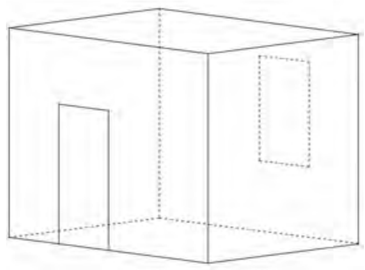


Figure 3.4 – Climate Consultant analysis. Temperatures ranges, temperature 3D chart, sun shading (summer) chart, wind well (June), psychrometric chart.

Table 3.1 – Model description for room performance simulation in future climate scenarios

MODEL DESCRIPTION	
	• Size of the rooms: 3 by 4 meters, 3 meters high (area: 12 m^2) • One door towards South (U=3,5 W/m^2K) • One window towards North (U=4,4 W/m^2K) • Primary use: residential (usage: 6.935 hours / year) • Intensity of use: medium (35m^2/pers.; 4 W/m^2; 4,5 W/m^2) • Natural ventilation (no cross ventilation possible) • Infiltration: 0,3 (Volumes/h) • No cooling and no heating • Brick model: floor slab (U=1,7 W/m^2K), concrete roof (U=1,8 W/m^2K), brick walls (all four are external U=1,4 W/m^2K), • Adobe model: floor slab (U=1,7 W/m^2K) adobe roof (U=1,8 W/m^2K), adobe walls (U=0,98 W/m^2K) • Weather dataset years: 1990, 2020, 2050, 2080 • Climate scenarios: A2 (business as usual), B1 (best-case)

As seen in the previous chapter, technological innovation has brought us to a point in which, for performing such an experiment, it is also possible to create digital models in which operative temperature is calculated by using Primero Comfort. One of the key aspects of BPSS is that weather files – available e.g., on the EnergyPlus website - are needed to simulate the performance of a building. While the weather files used for standard simulations are based on historical averages, there is also the possibility of using weather files based on future climate projections.

Recent studies have already used this methodology to investigate how climate change might impact thermal comfort and energy use in the future. While results differ depending on the primary use of the building and climatic conditions, the results are unanimous: while thermal comfort will decrease by the end of this century, annual energy demand is going to increase due to the need for cooling (Barbosa, Vicente, & Santos, 2015; Ciancio et al., 2019; Jylhä et al., 2015; Shen, 2017; Videras, Melgar, Cordero, & Andujar Marquez, 2020).

Besides research undergone by Fahmy et al. (2014) and Mahdy et al. (2013), no other similar studies done within the Cairene context are known to the author. Therefore, what follows is a brief experiment with a double aim; understanding the impact that a changing climate might have on the thermal comfort of a room in Cairo. Second, gaining a first insight into the effects of different building materials. The performance of two rooms differing only in the construction materials has been simulated with Primero-Comfort using different weather datasets representing Cairo historical and projected weather under different climate scenarios.

As already reported, the most recent scenarios developed by the IPCC are the ones described in the Fifth Assessment Report (2014). Because obtaining weather files that integrate these latest scenarios is still very expensive, scenarios A2 (business as usual scenario) and B1 (best-case scenario) developed in the Fourth Assessment Report (2007) were used. Even though they are not the most up-to-date files, they are easily accessible and are more than enough to get an insight. For this experiment they were created with the software Meteonorm (7.2).

The two rooms have been modelled as described in table 3.1. Both the digital room built in adobe and the one built in bricks have been simulated by using the following scenarios:

- Historical dataset (baseline) – year 1990 (averages 1960-1990)
- Scenario AR4-A2 (business as usual) – year 2020
- Scenario AR4-A2 (business as usual) – year 2050
- Scenario AR4-A2 (business as usual) – year 2080
- Scenario AR4-B1 (best-case) – year 2020
- Scenario AR4-B1 (best-case) – year 2050
- Scenario AR4-B1 (best-case) – year 2080

The digital models' simulation results have been assessed using two different methods: the first one indicates the percentage of fulfilled comfort hours by following the EN 15251 Standard, and the second one reveals the number of days in one year in which operative temperatures are above 29°C. It is helpful to use the EN 15251 Standard to get a first idea about the performance of the models. Nevertheless, some limits in it make it challenging to evaluate non-ventilated buildings in a hot and dry climate (Attia, 2012; Givoni, 1998).

By assessing the results with the second method, we consider that occupants of non-conditioned buildings have an adaptive behaviour that lets them adapt to higher temperatures. Without entering into details – we will do that in chapter five – we take the 29°C comfort boundaries expressed by Givoni for non-conditioned buildings as "acceptable conditions under still air" (1998) and as a *neutral condition of comfort*. All hours within days in which operative temperature is higher than 29°C are summarised and assessed.

3.4.1.1. Assessment of Fulfilled Comfort Hours According to EN 15251

In table 3.2, the results of the fourteen simulations have been summarised according to the three categories dictated by the EN 15251 Standard. By looking at the baseline of both models (1990 dataset), it is observable that fulfilled hours for the adobe model vary from 74,69 to 97,72% depending on the comfort class, while for the bricks model vary from 69,96 to 89,3%. When comparing these two models, the adobe model performs better than the brick model in each category: +4,7% in Cat. I, +9,3% in Cat. II and +8,4% in Cat. III. Even though the percentages might vary, the comparison of all other simulations follows this trend.

Figure 3.5 clearly indicates that even though there are differences between scenarios A2 and B1, the fulfilled comfort hours of both models decrease from year to year. When looking at the adobe room, in the best-case scenario (B1), comfort hours decrease by 2080 by 10,8 percental points, whereas in the business-as-usual scenario (A2), comfort hours decrease by 18,8 points. Similarly, in the bricks room, comfort hours drop by 7,9 points (B2) and 13,2 points (A1) by 2080. To make things clearer, having a 10% drop means an unfulfillment of comfort hours for about 693 hours per year (which equals to 29 days per year).

By comparing the same scenarios, the adobe model always has a higher number of fulfilled comfort hours. Nevertheless, it is interesting to see that the bricks model (in both scenarios) seems to have a curve that is slightly flatter than the adobe model – meaning that with time passing by and with temperatures rising more and more, the adobe model loses its performance more than the bricks model does. To have a better clue of why this might happen, it is necessary to look at the data from another perspective.

Table 3.2 – Adobe and bricks models - percentage of fulfilled comfort hours in different climate scenarios according to EN 15251 (Scenarios IPCC-AR4 / hours of use in one year: 6.935 = 100%)

			Comfort Class I (>=94%)			Comfort Class II (>=90%)			Comfort Class III (>=85%)		
Model	**Scenario**	**Year**	**Fulfilled [hrs]**	**Fulfilled [%]**	**Unfulfilled [hrs]**	**Fulfilled [hrs]**	**Fulfilled [%]**	**Unfulfilled [hrs]**	**Fulfilled [hrs]**	**Fulfilled [%]**	**Unfulfilled [hrs]**
ADOBE	Historical	1990	5180	74,69	1755	6174	89,03	761	6777	97,72	158
	A2	2020	4950	71,38	1985	5980	86,23	955	6695	96,54	240
		2050	4575	65,97	2360	5553	80,07	1382	6384	92,05	551
		2080	4187	60,37	2748	4874	70,28	2061	5796	83,58	1139
	B1	2020	4944	71,29	1991	5971	86,10	964	6740	97,19	195
		2050	4682	67,51	2253	5633	81,23	1302	6524	94,07	411
		2080	4512	65,06	2423	5428	78,27	1507	6417	92,53	518
BRICKS	Historical	1990	4852	69,96	2083	5526	79,68	1409	6193	89,30	742
	A2	2020	4713	67,96	2222	5364	77,35	1571	6055	87,31	880
		2050	4396	63,39	2539	5049	72,80	1886	5748	82,88	1187
		2080	4019	57,95	2916	4612	66,50	2323	5280	76,14	1655
	B1	2020	4709	67,90	2226	5350	77,14	1585	6091	87,83	844
		2050	4549	65,59	2386	5178	74,66	1757	5826	84,01	1109
		2080	4376	63,10	2559	4979	71,80	1956	5686	81,99	1249

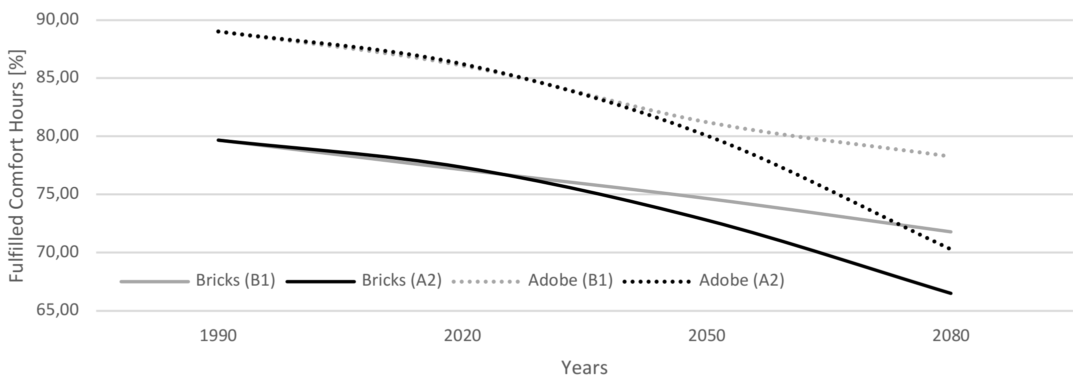


Figure 3.5 – Adobe and bricks models - percentage of fulfilled comfort hours in different climate scenarios according to EN 15251 - Cat. II (Scenarios IPCC-AR4 / hours of use in one year: 6.935 = 100%).

3.4.1.2. Assessment of Comfort Hours in Ranges Above 29°C

While a few days with operative temperatures (T_O) above 29°C might not be considered a big issue for most hot and dry climates inhabitants, a high number of such days (and nights) without taking measures to cool down the temperature can bring thermal discomfort (Givoni, 1998). By using the same results obtained with the fourteen simulations, the daily sum of hourly operative temperatures above 29°C – which we will consider as *neutral condition of comfort* - have been extrapolated from one year. In the upper graph of figure 3.6, it is possible to see the total number of days with T_O > 29°C for the 1990 dataset. What we can read from it, for example, by looking at the line indicating the bricks model, is that 33 days per year T_O > 29° for 19 hours, and 20 days

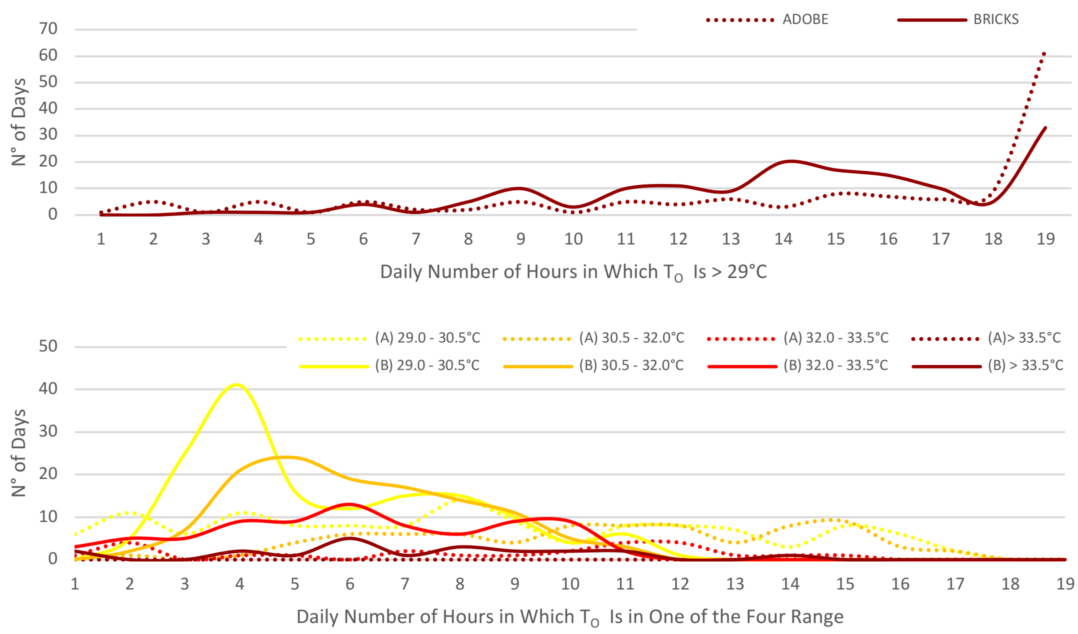


Figure 3.6 – Adobe (A) and bricks (B) models – number of days in which the operative temperature stays above 29°C (above) and within four ranges above 29°C (below). Historical data (1990).

per year, $T_O > 29$°C for 14 hours. By looking at the adobe model, the same happens about 63 days per year ($T_O > 29$°C for 19 hours) and three days ($T_O > 29$°C for 14 hours). Nevertheless, we still do not know if these hours are considered *slightly warm or very hot.* That means that we have no indication about the *severity of discomfort*.

In order to differentiate the *severity of discomfort*, these T_O hourly results have been divided into different temperatures ranges:

- Range 01 indicates a slightly warm condition (T_O is btw. 29-30,5°C)
- Range 02 indicates a warm condition (T_O is btw. 30,51-32°C)
- Range 03 indicates a hot condition (T_O is btw. 32,01-33,5°C)
- Range 04 indicates a very hot condition (T_O is higher than 33,5°C)

Looking at the bottom graph of figure 3.6, we can observe a much rounder picture by dividing the results by temperature ranges. The days in which T_O in the bricks model are > 29°C for four hours, for example, are now divided into 41 days in which T_O reaches the range between 29 and 30,5°C (*slightly warm)*, 21 days are *warm*, nine days are *hot*, and two days are *very hot (T_O > 33,5°C)*.

If we compare the two models of the bottom graph and look at differences within specific ranges, many interesting aspects emerge. In the bricks model, all four ranges of discomfort are reached. That means that temperatures above 29°C are within a *slightly warm* and *very hot* range, as mentioned in the previous paragraph. In the adobe model, on the contrary, the very *hot condition* is never met, and a *hot condition* is met for 24 days. By looking at the range 01 and 02, we can observe that in the adobe model, even though the number of days in which temperatures are met is lower than in the bricks model, the distribution of the daily number of hours in which that event occurs is higher. In other words, it seems that the adobe model performs better in keeping lower temperatures. Nevertheless, the number of hours per day in which the *neutral condition of comfort* is not met is higher than the bricks model.

While this aspect might give us already a hint about how construction materials perform differently under the same climate conditions, these first observations become more evident if we have a look at the performance of models simulated with climate projection datasets.

If we analyse the results summarised in figure 3.7 and figure 3.9 (A2 scenarios; 2020, 2050, and 2080 projection), we realise that in both bricks and adobe models, the number of hours in which a *neutral condition of comfort* is met decreases as time goes by. The bricks model unmet hours are distributed as follows: 2224 hours in 1990, 2501 hours in 2020, 2840 in 2050 and 3192 in 2080. The adobe model discomfort hours are distributed as follows: 2070 hours in 1990, 2435 hours in 2020, 2775 in 2050 and 3055 in 2080. This trend is aligned with the assessment done by using the Standard EN 15251. Moreover, what these results suggest for both models, is that the number of days in which *slightly warm* hours appear decreases, while *warm*, *hot,* and *very hot* hours increase year after year (made exception for the A2-2080 scenario in which *warm hours* decrease). In the bricks model results, the total number of *hot hours* are 484 in the 1990 baseline (78 days), 582 in the 2020 scenario (88 days), 720 in the 2050 scenario and 804 in the 2080 scenario (respectively 126 and 143 days). When we look at the same indicator for *very hot* hours, we find 150 hours in the baseline (21 days), 315 in 2020 (44 days), 621 in 2050 (66 days), and 1225 in the 2080 scenario (110 days). This trend is similar for the adobe model; as time goes by T_O increase constantly.

When looking at the results of the B1 scenarios as summarised in figure 3.7 and figure 3.10, we can observe similar but milder results. The bricks model unmet hours are distributed as follows: 2224 hours in 1990, 2489 hours in 2020, 2701 in 2050 and 2871 in 2080. The adobe model unmet hours are distributed as follows: 2070 hours in 1990, 2442 hours in 2020, 2650 in 2050 and 2811 in 2080. Similarly to the A2 simulations, also in the B1 scenario results, the number of days in which *slightly warm* hours appear decreases, while *warm*, *hot,* and *very hot* hours increase year after year. In the bricks model results, the highest increase in unmet hours appears within the *hot condition* range (484 hours in 1990, 635 hours in 2020, 725 hours in 2050, 812 hours in 2080) and *very hot* condition range (150 hours in 1990, 276 hours in 2020, 505 hours in 2050, 658 hours in 2080). In the adobe model, hot hours constantly increase (203 hours in 1990, 410 hours in 2020, 728 hours in 2050, 909 hours in 2080) as well as very hot hours (0 hours in 2020, 10 hours in 2020, 116 hours in 2050, 206 hours in 2080).As described previously, we can also see in the projected climate simulation that the distribution of discomfort hours per day differs from model to model depending on the construction material. Compared to the adobe models, in the bricks model, higher discomfort hours can be expected during more days of the year, while the number of hours per day in which this occurs is lower.

By looking a bit more into detail how outdoor temperature temperatures run during a three-day interval in summer (A2-2020 scenario), it is possible to understand much clearer what happens exactly to the T_O of the two models (figure 3.7). During this interval outdoor temperature varies from 23,7°-37,8°C (fluctuation = 14,1°C). The operative temperature of the bricks model fluctuates 5,1°C ($Tmin$ = 30,3°, $Tmax$ = 35,4°C), while the adobe model T_O fluctuates 2,6°C ($Tmin$ = 30,9°, $Tmax$ = 33,6°C). Again, it is observable that the adobe model can keep a slightly cooler and more constant temperature than the bricks model. In both simulations, all operative temperatures are higher than the assumed *neutral condition of comfort* of 29°C. Nevertheless, the bricks model, even though in the middle of the mornings achieves slightly lower temperatures than the adobe model, exceeds constantly temperatures above 33,5°C during afternoons and evenings.

As clarified by Fathy when referring to the study mentioned at the beginning of this section, these results can be explained by having a look at the thermal conductivity, the thickness and the thermal resistance of the materials (1986), and added to that, the resulting thermal transmittance of the composite construction. While the model shares the same floor material and a similar U-Value of the roof construction (bricks model = 1,8 W/(m^{2}K); adobe model = 1,77 W/(m^{2}K)), the walls of the adobe model have a thermal transmittance of 0,983 W/(m^{2}K), the ones of the bricks model have a thermal transmittance of 1,397 W/(m^{2}K).

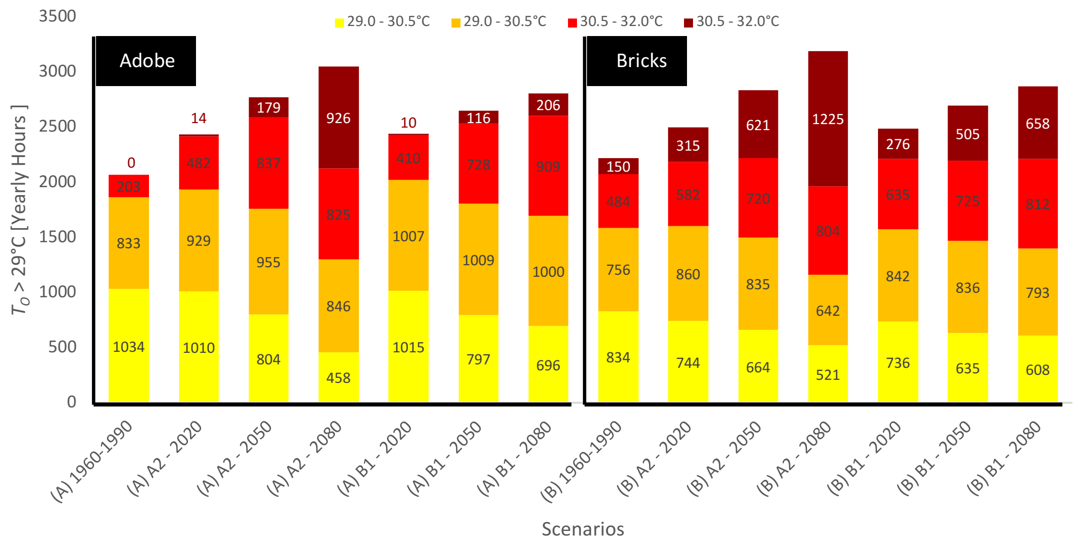


Figure 3.7 – Adobe (A) and bricks (B) models – Sum of yearly hours in which T_O > 29°C. Four range. All scenarios.

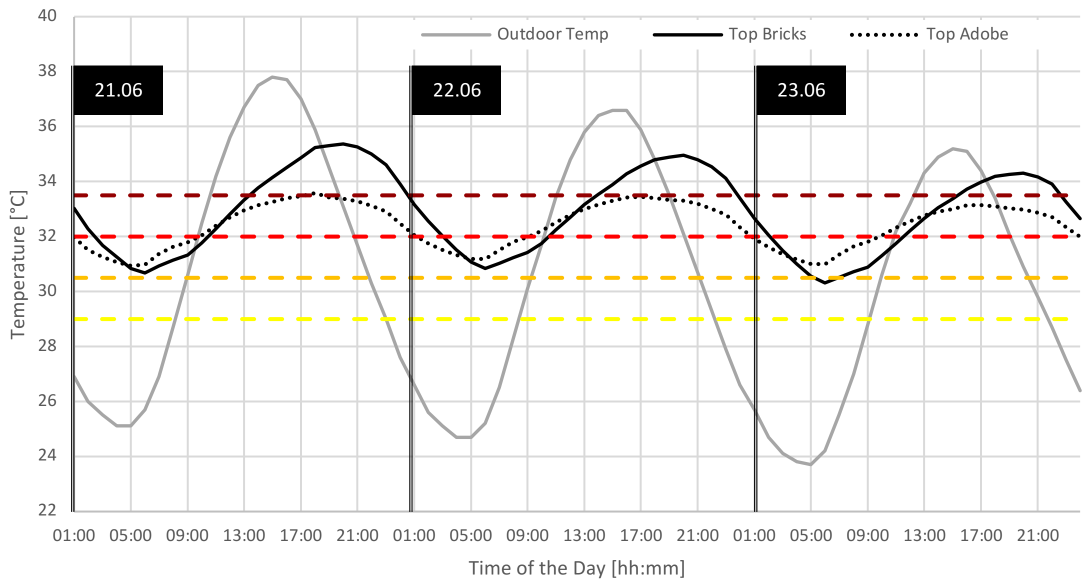


Figure 3.8 – Comparison of outdoor temperature, adobe model operative temperature and bricks model operative temperature – from 21.06 to 23.06. scenario IPCC-AR4-A2 / Year 2020. The four coloured lines indicate the four range thresholds.

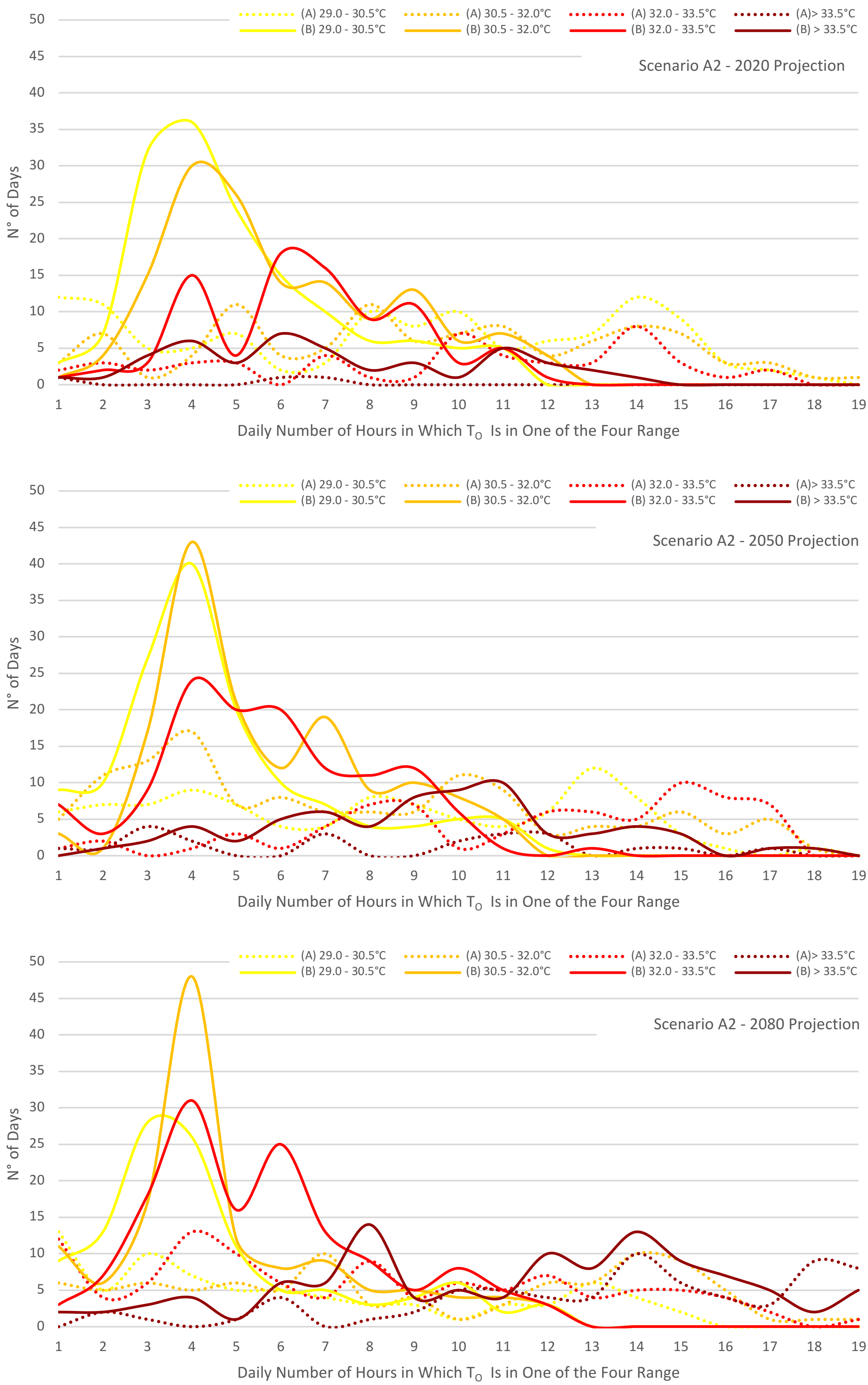


Figure 3.9 – Adobe (A) and bricks (B) models – Number of days in which the operative temperature stays within four range above 29°C. Scenario IPCC-AR4-A2.

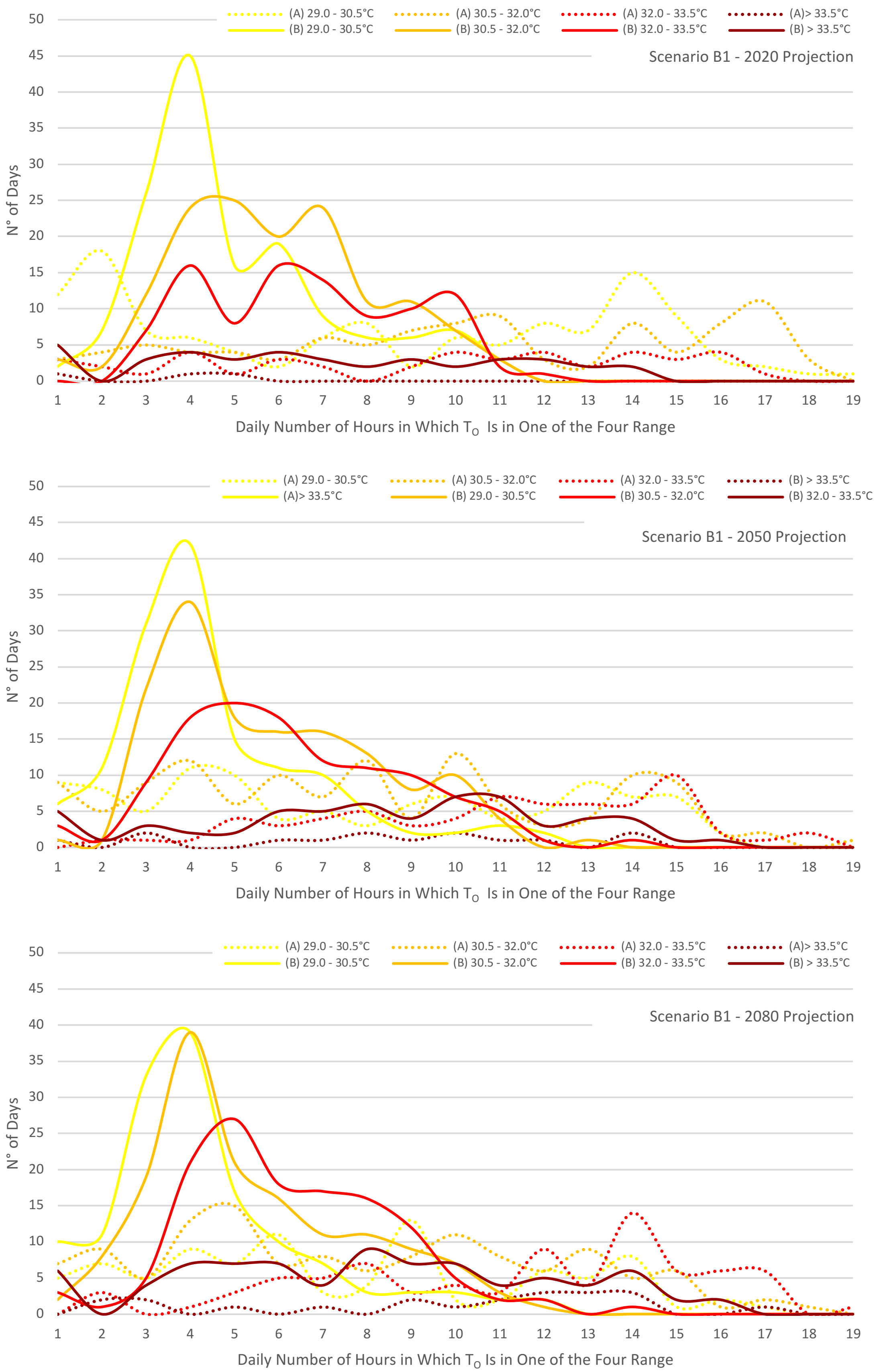


Figure 3.10 – Adobe (A) and bricks (B) models – Number of days in which the operative temperature stays within four range above 29°C. Scenario IPCC-AR4-B1.

3.4.1.3. Projected Performance of Two Rooms in the Greater Cairo Region - Conclusions

In this experiment, we looked at how climate projections might influence thermal comfort in buildings and how different construction materials may impact their thermal performance. Two digital rooms modelled with different materials have been simulated by using historical data (1990 baseline), different climate scenarios and their respective climate projections (AR4-A2 and AR4-B1; years 2020, 2050 and 2080).

The first evaluation method used (EN 15251) clearly showed that even though there are apparent differences between the *business-as-usual* scenario A2 and the *best-case* scenario B1, the fulfilled comfort hours of both models decrease from year to year. The comparison between the two models shows that the adobe model always has a higher number of fulfilled comfort hours. With the second evaluation method used, the outcome of the EN 15251 results have been confirmed. In addition to that, it has been observed that (with one exception) the number of days in which *slightly warm* hours appear decreases, while *warm*, *hot,* and *very hot* hours increase every 30 years constantly for both the bricks and the adobe model. So, while having an increasing number of hours in which the *neutral condition of comfort* is not met on a yearly basis, a shift towards higher temperatures can be observed. The bricks model constantly reaches higher operative temperatures for a shorter number of hours. A higher number of operative temperatures higher than 29°C can be expected during more days of the year than the adobe model. Nevertheless, even though the adobe model can keep slightly cooler and more constant temperatures than the bricks model, it seems that temperatures remain higher than the *neutral condition of comfort* for longer.

When observing operative and outdoor temperatures of three summer days, the adobe model (0,983 $W/(m^2K)$) has a low T_O fluctuation and keeps the temperature lower during the warmest hours of the day. The bricks model (1,397 $W/(m^2K)$), even though in the early morning can bring T_O lower than the adobe model, reaches higher temperatures in the late afternoon. While there might be other causes as well, it seems that thermal transmittance of the walls is primarily responsible for the different temperature outcomes.

After having seen how the geographic and climatic conditions are affecting Cairo and its inhabitants, and might do so in the future, the next chapter will bring us nearer to another important aspect of this research: Cairo informal urban development.

4. Cairo: a Short Introduction to its Informal Urban Development

In the previous chapter we have been able to understand the natural context in which Cairo finds itself and, by delving into climate projections, we explored some of the consequences that increasing temperatures might have in relation to thermal comfort. As already mentioned, buildings are embedded into a context which is influenced by the local geography and climate and is moulded by local socio-economic conditions. The aim of this chapter is to give an overview of the urban development that transformed the Egyptian Capital into one of the biggest and densely populated areas in the world. Understanding the recent history of the city will let us comprehend the magnitude of importance that informal buildings have in the Cairene urban context.

While this is meant to be a general summary covering the last 70 years of Cairene urban development, the reader that would like to study the matter into detail should have a look at the recent publications by David Sims, Yahia Shawkat, and Angelil & Malterre-Barthes. The American economist, urban planner and Cairene resident David Sims is able to portray and map Cairo's city history and its informal urban processes in the book *Understanding Cairo: the logic of a city out of control*. He argues that the megacity "can be considered a kind of success story, in spite of everything" (2012). Yahia Shawkat, an Egyptian researcher and planner, in *Egypt's Housing Crisis: The shaping of urban space*, digs into the Egyptian housing policies and legislation written over the past 80 years, arguing that without "neoliberal deregulation, crony capitalism corruption and neglectful planning", affordable housing would be less hard to achieve (2020). In the book *Housing Cairo: the ~~informal~~ response* (2016), Angelil & Malterre-Barthes reported the results of a research done in Ard al-Liva focusing on the informal architecture and its processes. By using a language mostly well understood by architects and planner, the authors are able to put informal processes in context using different narratives and by taking different approaches while including valuable contributions from an interdisciplinary variety of local experts.

From a global institutions' perspective, the following books and reports might be a good start. The book *Cairo's Informal Areas between Urban Challenges and Hidden Potentials*, published by the GTZ, gives a complete overview on informal areas and its stakeholder (Kipper & Fischer, 2009). *Cairo: a city in transition* is a contribution published in 2011 by U.N. Habitat in collaboration with the American University in Cairo (Social Research Centre). The main focus of this report is the assessment of a socio-economic survey results' (n=4.000) that helps in getting a picture of Cairene dwellers. The report covers themes such as composition and density in households, housing quality and durability, water and sanitation, security, municipal solid waste management, education, transportation, employment and informality, access to health, expenditures and income in Cairo (U.N. Habitat, 2011). Lastly, in 2016, the German Advisory Council on Global Change was able to explore and summarise some of the special challenges and opportunities that Cairo might face in this Century in its path to transform towards sustainability (WBGU, 2016).

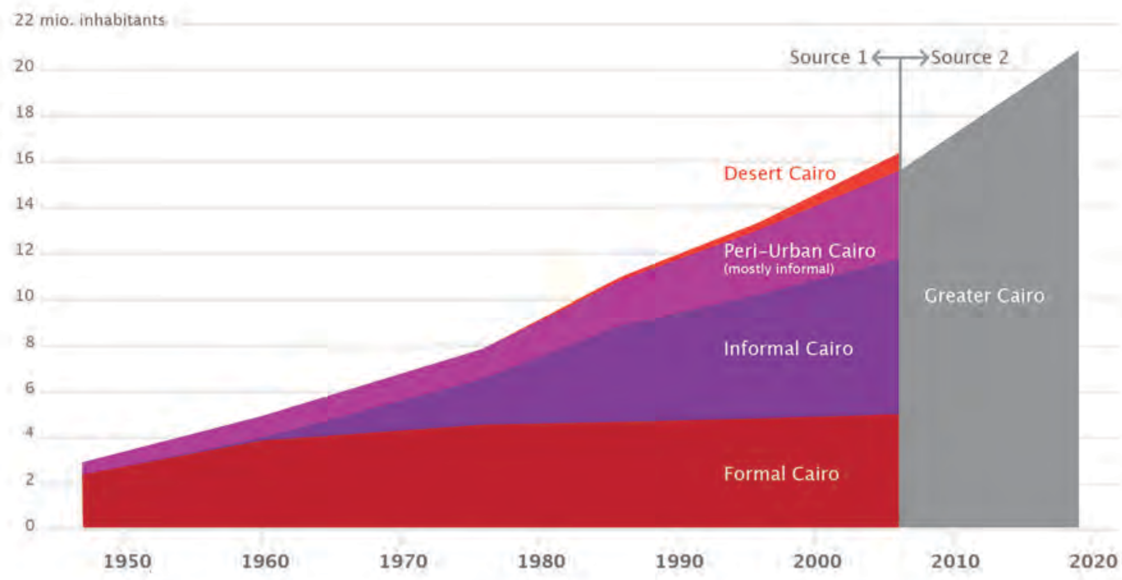


Figure 4.1 – Evolution of the population of Greater Cairo and its component parts. Adapted from the following: Source 1 (Sims, 2012, p. 83); Source 2 (CAPMAS, 2019b, 2019a, 2019c).

4.1. Cairo: a portrait of its recent years

Cairo has a millenarian history, and its traces can be found in and around the city. In the collective imaginary, when thinking about Egypt a first thought might go directly to the *Pyramid of Giza* – the oldest of the Seven Wonders of the Ancient World – that "sits" on the desert sand since 4.500 years. Other thoughts might go to *historic Cairo* (also referred as Islamic Cairo), in which residential buildings, mosques and mausoleums inherited by the Islamic dynasties over the course of about 1.300 years can be found in abundance (Behrens-Abouseif, 1989; Yeomans, 2013). UNESCO included in 1979 both Memphis, with its Necropolis and Pyramids from Giza to Dahshur, and historic Cairo in its World Heritage List, as a recognition of the fact that "Cairo's architectural monuments ranks amongst humanity's great achievements" (Behrens-Abouseif, 1989, p. 3; UNESCO, 2020).

The historical heritage of the Egyptian megacity, nevertheless, covers only a very small percentage of buildings and settlements that are part of the Greater Cairo Region (Sims, 2012, p. 10). By looking at the evolution of population in the figure 4.1, with a population growth that went from about 2,5 million in 1946 to more than 20 million in 2019, it can be assumed that most of the buildings embedded in today's Cairo's urban landscape were built during the last seventy years. This rapid urbanisation led to an incredible high demand for housing that could not be met either by the government or by private formal initiatives. So, how have Cairenes responded to this situation? Well, to put it simple, with informality and self-built buildings (Angelil et al., 2016; Shawkat, 2020). While there are different definitions of informal (or unplanned) development, in this context we might borrow the one summarised by Sims as the "results of extra-legal urban development processes […] that exhibit a complete lack of urban planning or building control" (2012, p. 95). Today more of 60% of Cairo's dwellers are assumed to live informally, and according to estimates done in 2008 approximately 53% of the built residential surface of Greater Cairo is informal (Kipper & Fischer, 2009; Séjourné, 2006; Sims, 2012; Sims & Séjourné, 2000; U.N. Habitat, 2011). As David Sims puts it, "it is thus no exaggeration at all to say that almost all of today's Greater Cairo is the product of informal processes, that these processes are dominant, and that they will continue to dominate for years to come" (2012, p. 86). In the next few paragraphs, we will explore how these processes have expanded throughout the years, and in addition to that, we will delve into the aspects that characterize informal areas and buildings in the Egyptian capital.

4.1.1. Parallel Cities and Urban Types

While having a highly heterogenous cityscape, in Greater Cairo there are three specific urban types, that just as "parallel cities" that share the same boundaries, have been developing since the 1960s and the 1970s: the *formal urban areas*, the *informal urban areas* and the *new desert cities* (also known as satellite cities). These urban types, or "cities", are subject to different governance and economic structures and differ in their social organisation and urban design (Sims, 2012; WBGU, 2016).

In figure 4.2 it is possible to see Cairo's built-up area in 1950. Here, the entire urban area is considered to be either developed legally under a statutory planning regime or has grown historically over a long period of time, and therefore is considered *formal*. In the 1950s, the massive industrial development policy launched by President Nasser attracted migrants from Upper Egypt and the Delta. This caused critical housing pressures, and while the government invested in social housing, most of the new urban dwellers went to live in the old-town districts, by renting a room or a shared flat. After years of savings, some, thanks to lower prices in Giza Governorate, were able to buy land on the fringes of the city and built a home (Kipper & Fischer, 2009; Sims, 2012; WBGU, 2016).

The first expansion phase of *informal settlements* takes place between 1960-1966. During this time Greater Cairo population increased at a 4,4% yearly rate. While Nasser's housing policy was not adequate to solve the crisis, low-income families found accommodation in informal settlements in the northern and western parts of the city (Abdelhalim, 2010; Kipper & Fischer, 2009). Most of the settlements were built on agricultural land - against which in 1966 the state started reinforcing legislation forbidding construction -, some were built on desert land belonging to the state (Kipper & Fischer, 2009).

During the period between the 1967-1973, while focusing on different conflicts and wars, the Egyptian state disengaged both from the development of the city infrastructure and housing construction (Kipper & Fischer, 2009). Once the conflicts decreased, the situation changed quite rapidly, as soon as President Sadat introduced the *Infitah*, the "opening the door" policy in 1974. This new policy, departing from Nasser's socialist-inspired ideas, led Egypt and Cairo be the protagonist of a first real-estate boom that transformed the cityscape with new office buildings, tower blocks, housing for higher-income groups and infrastructure such as motorways, metro, sewage system (Sims, 2012; WBGU, 2016). Besides opening the economy to private investments, the *Infitah* permitted Egyptians to travel more freely, and to emigrate in countries in which manpower was needed and salaries were higher as in Egypt. It is assumed, that most of the savings generated by Egyptian manpower in the Gulf States during the oil-boom (1973-1979), were invested in informal land and buildings. Once again, while the private and public sectors were not able to meet the housing demand for poor and middle-class families, informal districts expanded, and by the end of the 1970s 84% of new housing units were considered illegal. (ABT Associates Inc., Dames and Moore Inc., & General Organization for Housing, Building, 1980; Kipper & Fischer, 2009; WBGU, 2016).

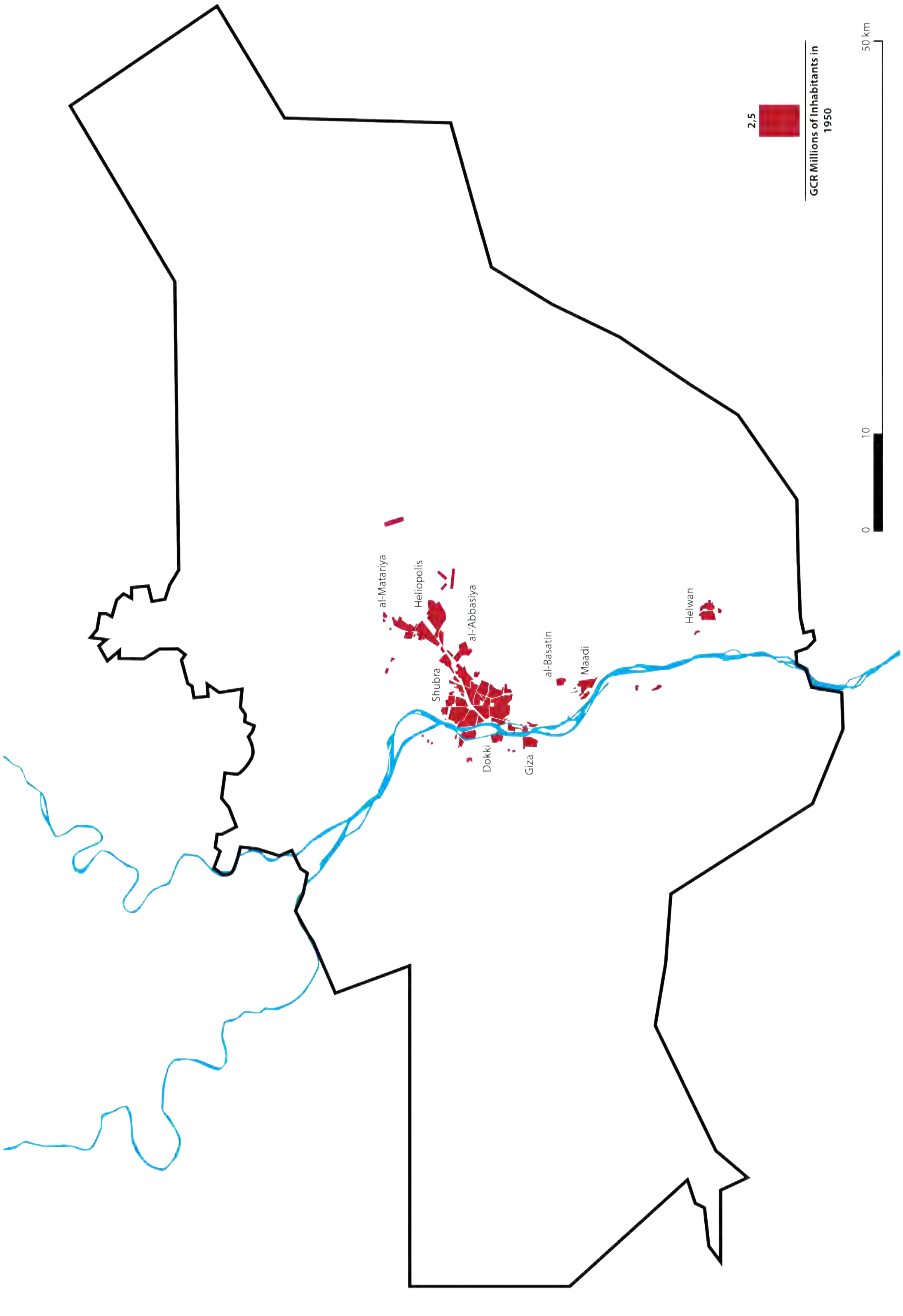


Figure 4.2 – Built-up area of Cairo in 1950. Adapted from Sims (2012, p. 47)

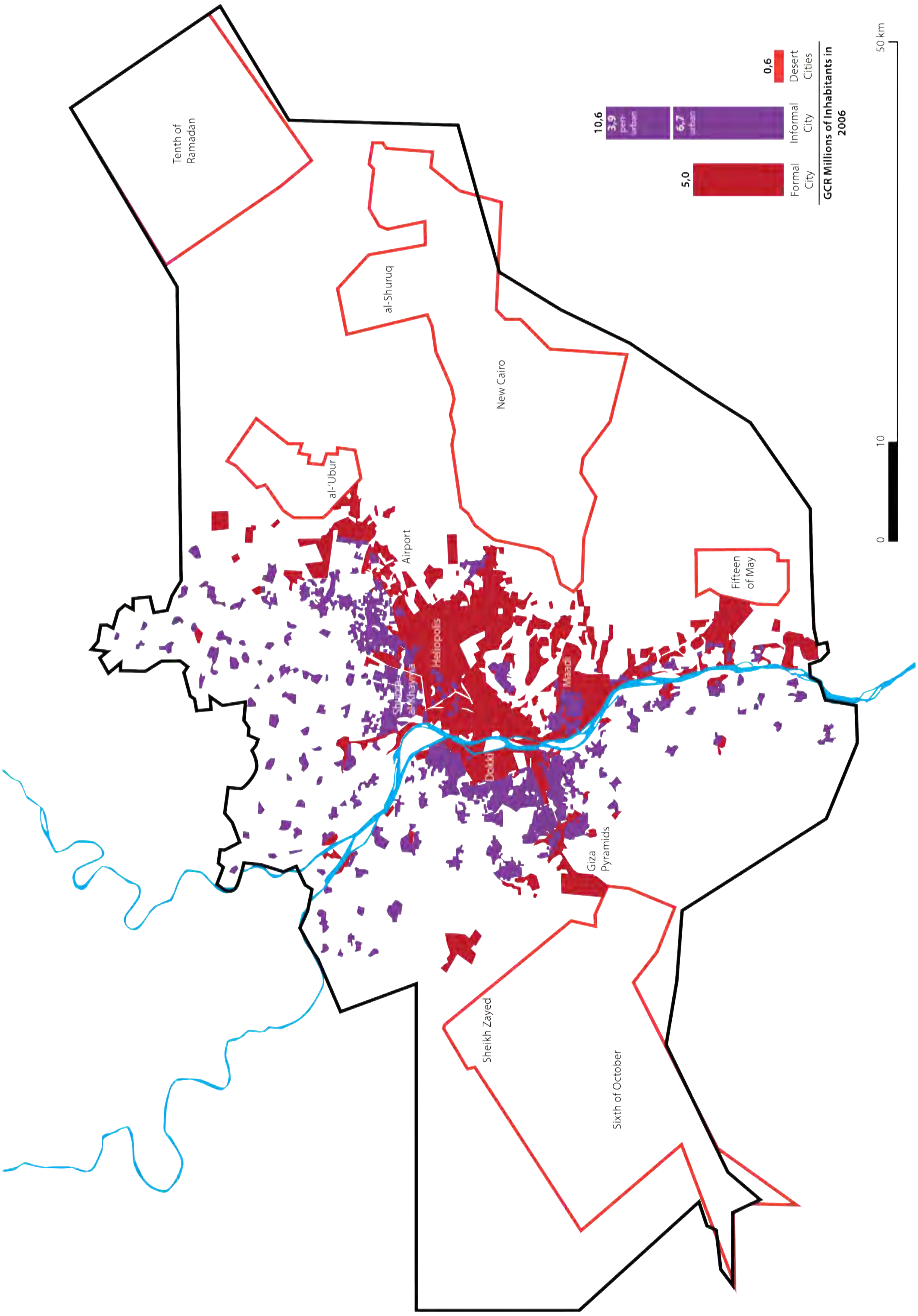


Figure 4.3 – Greater Cairo formal and informal cities. Adapted from Sims (2012, p. 48,60).

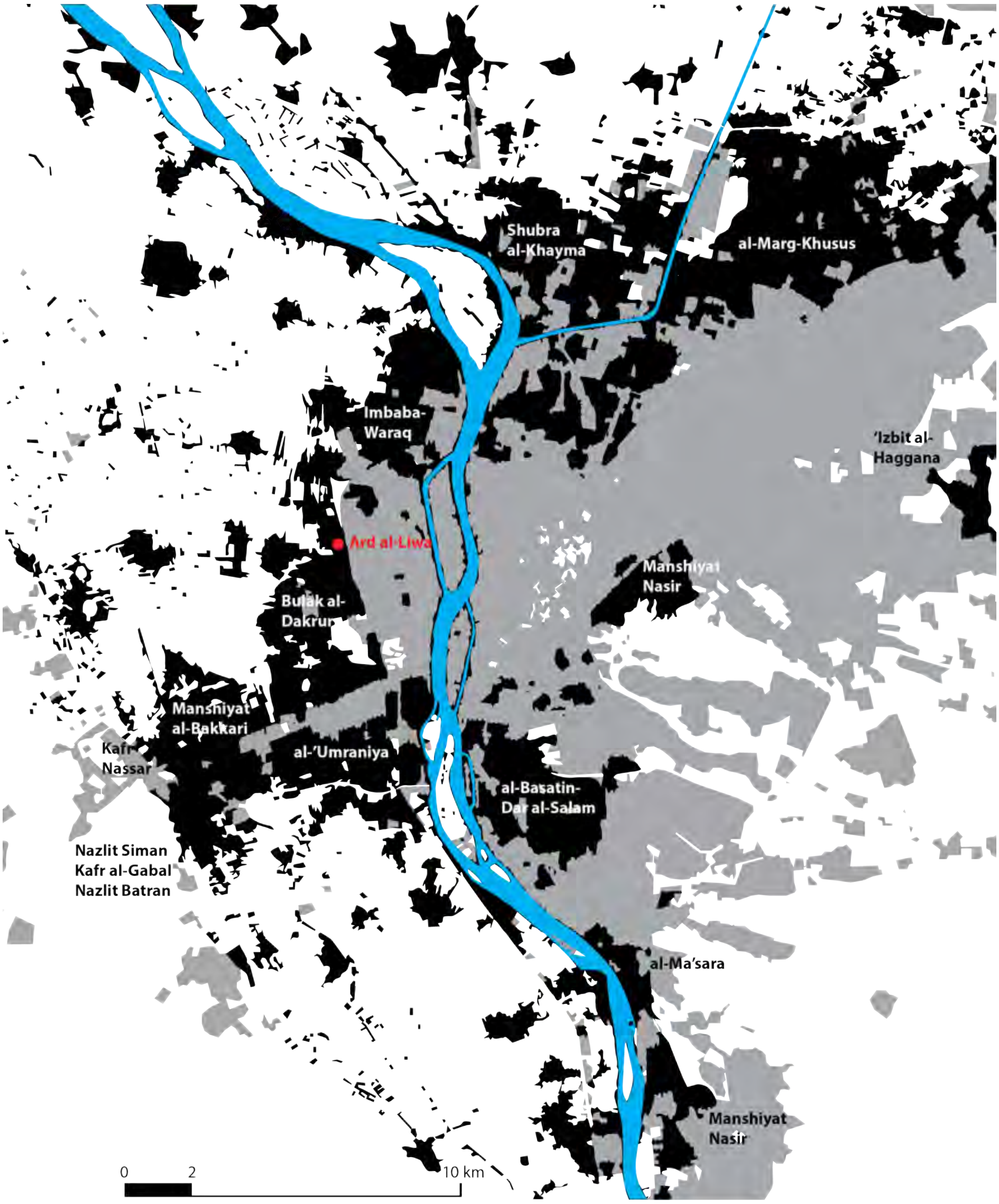


Figure 4.4 – Large informal areas in Greater Cairo in 2008. Adapted from Sims (2012, p. 60,127).

Figure 4.5 – Visual comparison of building density: the railroad divides informal (left) and formal areas. Source: Google Earth Pro (2018b).

In 1977, as the city population went on growing - mostly informally - Sadat introduced the *New Towns policy* to address both the housing crisis as well as the urbanisation on agricultural land. The idea behind this policy, was to relocate and settle the growing population in new satellite cities in the Cairo metropolitan Area. On the basis of the New Town programme the following cities were planned: 6th of October, 10th of Ramadan, 15th of May, al-Ubur, al-Shuruy, Sheikh Zayed, New Cairo and al-Badr (Kipper & Fischer, 2009; WBGU, 2016).

In the beginning of the 1980s the Iran-Iraq War and the oil prices caused a decline of the Egyptian emigration towards oil countries. Rural migration almost stopped and the demographic growth rate contracted from a 2,8% to a 1,9% per year in the 1976-1986 period (Bayat & Denis, 2000; Sims & Séjourné, 2000). While the formal city and the desert cities slowed down their urban development, the informal city extended, densified and continued to grow at an estimated rate of 3,2% per year (Kipper & Fischer, 2009). Again, while the implementation of the public housing policies as well as the new towns policy were failing, the informal sector has "greatly benefited the urban poor, both in producing a massive amount of housing which offered a range of choices affordable to most if not all, and in allowing those of the poor with at least some equity to participate in the process and enjoy its rewards" (Sims, 2002).

During the 1980s and the 1990s the largest informal settlements started to being noticed by the government. While authorities began to provide basic services to these so-called *'ashwa'i* or *'ashwa'iyyat* (random, unplanned, disordered), they also continued to prohibit construction on agricultural land. Nevertheless, this happened only after Islamic movements became active in these areas and started actively to provide services before the government. The awareness of the informality phenomenon increased even more when, after about 15 years of construction, the Cairo Ring Road was completed in 2001. From this point in time the "massive reddish-hued informal housing areas stretching far into agricultural plain" would no longer being dismissed as "marginal aberration" (Sims, 2012, pp. 68–69). Figure 4.3 shows to which extends informality has "filled" the map of Greater Cairo in 2006 and figure 4.4 shows the larger informal settlements.

In 2009 the government, tolerating de facto a "quasi-formal" status, classified informal settlements as "unplanned areas", giving its dwellers the chance to finally end fearing eviction, and to claim a permanent right to keep their domicile if certain conditions were met (Abdelhalim, 2010; Khalifa, 2011; Sejoume, 2012). After the Revolution in 2011, it can be assumed that the number of people living in informal has been rising further, as it has been observed that construction in these areas increased strongly (Sims, 2013, p. 73). While the core of the formal city is emptying, and satellite cities continue to not meet the expectations of the government's visions born in the 1970s, some of the informal areas have reached saturation. It is possible to assume that be the biggest informal expansion will continue to happen in the peri-urban frontier of the megacity exceeding a population of 7,5 million persons by 2026 (Sims, 2012, p. 134).

Informality is a phenomenon stigmatised globally, yet why it does seem that informal processes have proven to stand the test of time in Cairo consistently? While in the previous pages we understood how informality became the dominant mode of living in Cairo, in the following pages we will answer this question by discussing their characteristics, as well as the advantages and disadvantages of living informally.

4.2. Characteristics of Informal Settlements in Greater Cairo

When thinking about informal areas, slums, “shacks and shantytowns” might come to mind as we mostly known them from Latin America, Asia and Africa (Sims, 2013). Those areas might lack basic infrastructure such as sanitation and clean drinking water, the dwellings might be built with improvised or unstable materials, and they might be unsafe because are built on unsuitable sites (e.g., solid waste dump sites). Sometimes, these areas might also be known or perceived as “nasty, brutish and short” (Khalifa, 2011; U.N. Habitat, 2011).

Quite differently, even if it is still possible to encounter small slums pockets or unsafe areas as just described, the vast majority of informal settlements’ housing stock in the Arab countries is made up of small footprint apartment blocks and multi-storeys houses. They are durable and well-built, covers the needs of families that look for affordable solutions, and do not reflect absolute poverty by international standards (Sims, 2013; U.N. Habitat, 2011; WBGU, 2016).

In Cairo, the most known type of informal settlement has a high building and population density (see figure 4.5), and while some high towers might exist, most of the brick and reinforced concrete buildings have an average height of five to eight floors and are solidly built. Although the standards might be lower than in formal parts of the city, basic infrastructure is present (WBGU, 2016). While some variations are possible, three predominant types of informal settlements can be recognised in Greater Cairo: built on private agricultural land, built on state owned agricultural land, and built on state owned desert land. According to a study done in the 2000, in Greater Cairo about 83% of informal areas were built on what was privately held agricultural land. The rest was developed on land controlled by the state: about 7% on reclaimed agricultural land, and about 10% was built on desert land (Sims & Séjourné, 2000).

Many researchers share the opinion that, at least for people struggling for a decent livelihood in Cairo, these areas and buildings have more advantages than disadvantages (Sims, 2012, 2013; U.N. Habitat, 2011; WBGU, 2016). Clearly, the first advantage of living in an informal building is its affordability. Historically, due to the fact that no corporate entities, banks or government are involved, the process of building a dwelling in an informal area is incremental and depends on the monetary resources at disposal of the family acting as owner and builder. Although in terms of floor-area ratios and building heights a high exploitation of land parcel is possible, the building process might be slower than in formal areas (Sims, 2013). It may pass by some years between the purchase of a small parcel of land -at the fringes of the city, because it is much cheaper than in formal areas- and the actual construction, and often construction is carried out floor by floor, or room by room, and takes several years (Angelil et al., 2016; Sims, 2013). Buildings that look unfinished due to the undecorated façades and the reinforcement bars projecting out of the last (inhabited) built floor are not an exception.

The construction process involves as few middlemen as possible and it is usually supervised and carried out directly by the family itself, with help of relatives or unregistered labourers. The design process follows standard designs that, while fulfilling the user needs under the given spatial pressure, evolved during decades of testing (U.N. Habitat, 2011). Thanks to this process, building an informal dwelling costs 30-50% less than a formal one, and rental costs can be about 20% less expensive in informal houses (Sims, 2013; U.N. Habitat, 2011; WBGU, 2016).

Figure 4.6 – On the roof of a Cairene informal settlement (Photo G. Vignola)

Another important characteristic that brings benefits in informal settlements, is to be found on the ground floor of many – if not most of – informal buildings. Here, commercial activities, manufacturing, small-scale artisanal industries and other services are common, and in more mature settlements, these businesses can generate a significant number of jobs and economic opportunities (Sims, 2013; U.N. Habitat, 2011).

This adds another layer of positive aspects related to informal areas. The mixed-use character of the buildings and the clever use of the streets and alleys for markets and commercial activities supports the daily needs of its informal dwellers, while strengthening its social networks. Walkability and "home-work" proximity, as seen in Boulaq al-Dakrour for example, where 60% of residents go to work on foot, let Cairenes dwellers saving time to commute, as well as saving money and energy (Kipper & Fischer, 2009; WBGU, 2016). Does not that remind us of some of the common aspects taught nowadays by planners, architects, and advocates for sustainable urban development?

Besides being built by violating the standards and regulation of building laws, there are other facets in which informal settlements show disadvantages when compared to formal areas. Basic services such as supply of decent quality water supply, garbage collection, public transportation, sanitation and sewerage connections, electricity, educational and health services, police presence, are often lacking or have a poor quality. In addition, these high-density built areas, lack urban open spaces such as parks and plazas, and paved and lighted roads are still missing in most of informal areas. As one might imagine, adding basic services once that a whole district has already been built can be time-consuming and costly (Kipper & Fischer, 2009; U.N. Habitat, 2011). On the other hand, it is also important to mention that while informal areas have been neglected by the government for many years, issues with solid waste management, electricity or water cuts are increasing also in areas of the city considered formal or with high-income inhabitants such as Nasr City or Mohandseen (U.N. Habitat, 2011).

Although it has already been said that buildings are well-built and durable (also thanks to their concrete reinforced skeletons and brick walls) there are some aspects that can be problematic.

Typically, informal buildings have a smaller footprint of the ones in formal areas, and while having three blind facades, openings are placed on the façade towards the street. Additional smaller openings are found in shafts that are either attached to the staircase or on the sides connected to the adjacent buildings (Angelil et al., 2016; U.N. Habitat, 2011). When considering also that the streets that offer access to the buildings are very narrow, it becomes clear that these dwellings are often poorly ventilated and do not get enough access to natural light (Kipper & Fischer, 2009; Sims, 2012; U.N. Habitat, 2011). Furthermore, buildings are hardly shaded and poorly insulated, meaning that they are cold in winter and hot in summer (Sims, 2012; WBGU, 2016). As we have discussed in the chapter *Climate Projection and Their Influence on Thermal Comfort in Cairene Buildings*, even though this aspect already impacts the inhabitants' quality of life today, it will be even more problematic in a future in which higher temperatures are expected.

But again, this should be seen as a larger issue extended to formal dwellings as well. And this might happen because of two major causes. First, the majority of construction firms still ignores sustainable and resource efficiency construction methods; and second, after more than ten years after launching the Egyptian Green Pyramid Rating System (based on LEED - Leadership in Energy & Environmental Design) the government has not been able to enforce such system or to launch funding programmes for energy saving in the construction field (Moussa, 2019; WBGU, 2016).

4.3. Lesson Learned

Clearly, while touching upon advantages and disadvantages of most of the facets related to the urban and architectural context of informal areas, a generalist approach was taken. Therefore, it is important keep in mind that informal areas and dwellers are very heterogenous and are different from one another (Kipper & Fischer, 2009; Sims, 2012; U.N. Habitat, 2011). The report *Cairo's Informal Areas between Urban Challenges and Hidden Potentials*, was able to sneak peek into the lives of informal settlers, showing how different lives take place under informal circumstances. By portraying street vendors and judges, government employees and artisans, workshop owners and doctors revealed the wide spectrum of socio-economic groups embedded in these areas (Kipper & Fischer, 2009).

And probably it is also this heterogeneity one of the keys that let informal areas continue to develop and grow standing the test of time. In informal areas the dwelling supply reflects the variety of the demand and, as explained by Kipper and Fischer "the location, dwelling size, and neighbourhood design are shaped by what people need most, accommodating variety in household size, priorities, and lifestyles" (2009, p. 40). While informal settlements have been marginalised, and have been lacking government's support for decades, they have proven to work as "self-help housing mechanism" by self-financing and constantly incrementing their development. These areas and their dwellers might need more urban open spaces, better infrastructures, improved services, and a healthier living environment. Nevertheless, the compactness of the urban built form and the mixed use of the buildings and streets enable self-sufficiency and high-efficiency, things that hard to be found in the desert cities and in other formal districts planned in recent years (Kipper & Fischer, 2009).

5. Cairo: Chasing the Vernacular

In the last two chapters, we have been able to put informality and informal buildings into perspective. We have discussed issues related to a changing climate in Cairo. We understood that this dominant mode of living, rooted in a well-functioning informal socio-economic system, will continue to thrive and expand, at least for the next decades.

In the next part of this research, the focal points will be informal dwellings and the building scale. We will embark on a study in which Cairene homes built in different eras will be compared and their performance assessed. We will see how, and to what extent, learnings from dwellings constructed in the past might be helpful to optimise informal buildings to meet end users' thermal comfort expectations while being environmentally sound.

Nowadays, added to the issues mentioned in the previous chapters, megacities like Cairo cannot cope with a steadily increasing energy demand. The energy supply in the Cairene residential sector has been in a crisis for years; even though 99 per cent of the buildings are connected to the public electricity network, between 11 and 22 per cent of households experience constant power interruptions (U.N. Habitat, 2011). As reported by the Ministry of Electricity and Renewable Energy, in 2019, the residential sector in Egypt was responsible for about 48 per cent of the share of energy distributed (60.115 GWh) (Egyptian Electricity Holding Company, 2019a, p. 84). This number, which was about 40 per cent in 2009 (47.431 GWh), is steadily growing due to the "expansion of residential compounds [...] and the widespread use of domestic appliances, especially the air conditioners in the summer" (Egyptian Electricity Holding Company, 2011, 2015, 2019b).

Why should the observation of vernacular architecture be of help? Well, we hypothesise that the buildings that made it through decades and centuries to this day have been able to pass the test of time sustainably. And in addition, they have been able to comfort their inhabitants before the era of air-conditioning and cheap-fuel heating by using adaptable and low-technology solutions (Lavafpour, 2012; Roaf et al., 2005, p. 152). What follows does not want to be a discussion in which sympathisers of traditional buildings wish to prove how modern architecture is bad, ugly, unsustainable, and superficially show how "traditional buildings are more sustainable."[15] (Design Build Network, 2007; see also Holland, 2017; Moore, 2020). What we want to understand is, by learning from design strategies and passive systems used in the past, if there might be a chance to indicate what measures can be taken to improve the comfort and reduce the energy consumption of informal buildings - that, as it will be argued later, might be seen as contemporary-vernacular.

Vernacular architecture still occupies a marginal position in architectural research (Asquith & Vellinga, 2006; Chandel, Sharma, & Marwah, 2016). Nevertheless, although this field is relatively young, the number of studies and publications that deal with it seems to increase year after year. One of the first references to the field was done in 1964 when Bernard Rudofsky showed the exhibition *Architecture Without Architects* at NYC MoMa (followed by a publication)

[15] A good basis to go through vernacular and contemporary architecture topics are the following book chapters: *Traditionalism and vernacular architecture in the twenty-first century* (Asquith & Vellinga, 2006) and *The failure of modern buildings* (Roaf et al., 2005).

and received much support from well-known architects such as Walter Gropius, Jose Richard Neutra, Gio Ponti, Kenzo Tange (see Rudofsky, 1965).

While other important works might be mentioned (such as Amos Rapoport works), it was only in the 1990s that vernacular architecture would be brought to a broader audience; with the publication of Paul Oliver's *Encyclopaedia of vernacular architecture of the world* (see Oliver, 1997b, 1997c, 1997a). The impressive collection of vernacular examples and summary of principles, theories, and philosophies from all over the world has been undoubtedly a reference work used by researchers in the field. Furthermore, in the *Encyclopaedia*, we find one of the most used definitions for vernacular architecture - definition that we are going to use as a basis also for this research:

> *Vernacular architecture comprises the dwellings and all other buildings of the people. Related to their environmental contexts and available resources, they are customarily owner- or community-built, utilising traditional technologies. All forms of vernacular architecture are built to meet specific needs, accommodating the values, economies and ways of living of the cultures that produce them* (Oliver, 1997a, p. xxiii).

Like almost any other research field, one can recognise two significant approaches in which vernacular architecture is studied. The first way is *theoretical* and follows an *inductive method*. With a mix of anthropological and architectural knowledge and acumen, existing buildings (or what remains from them) can be explored to understand how and why they have been built the way they are. The three steps involved in using this method are: 1) observe, 2) observe a pattern, 3) develop a theory. Although this method permits generalising and developing theories about strategies and principles related to internal comfort and energy needs, a final conclusion cannot be proven but can be invalidated (Streefkerk, 2019). While some researchers in our field might focus on environmental and building performance issues only, in some cases also socio-economic conditions are included in the findings (e.g. Badr, 2014; Lavafpour & Surat, 2011; Mohamed & Ali, 2014; Raof, 2018; Soleymanpour, Parsaee, & Banaei, 2015). Another way to study vernacular buildings is *empirical.* By using the *deductive method*, a hypothesis based on an existing theory is tested. By analysing the results of the test, the hypothesis is either supported or rejected. The steps involved in this kind of method are: 1) start with an existing theory, 2) formulate a hypothesis based on that theory, 3) collect data to test the hypothesis, 4) analyse the results and support or reject the hypothesis (Streefkerk, 2019). In the case of our research field, energy performance is either tested with the help of Building Performance Simulation Software, with field measurements and monitoring, or with computations (e.g. Abdel-Aal, Maarouf, & El-Sayary, 2018; Kubota & Toe, 2015; Saleh & Saied, 2017; Zhai & Previtali, 2010).

There are also publications (e.g. Roaf et al., 2005; Weber & Simos, 2014) in which both the *theoretical* and the *empirical* approaches are used. When looking into buildings and hot climates research, probably one the most cited ones is *Natural energy and vernacular architecture - Principles and examples with reference to hot arid climates* published in the 1980s by Hassan Fathy, one of the best-known Egyptian architects (1986). By distancing himself from the "international design from buildings that must be used in all countries and all climates", he summarised the principles used in vernacular architecture to cope with hot and arid climate (hot summers, mild winters, little precipitations). He showcased a wide range of practical and local examples built during the course of centuries (Fathy, 1986, p. xviii).

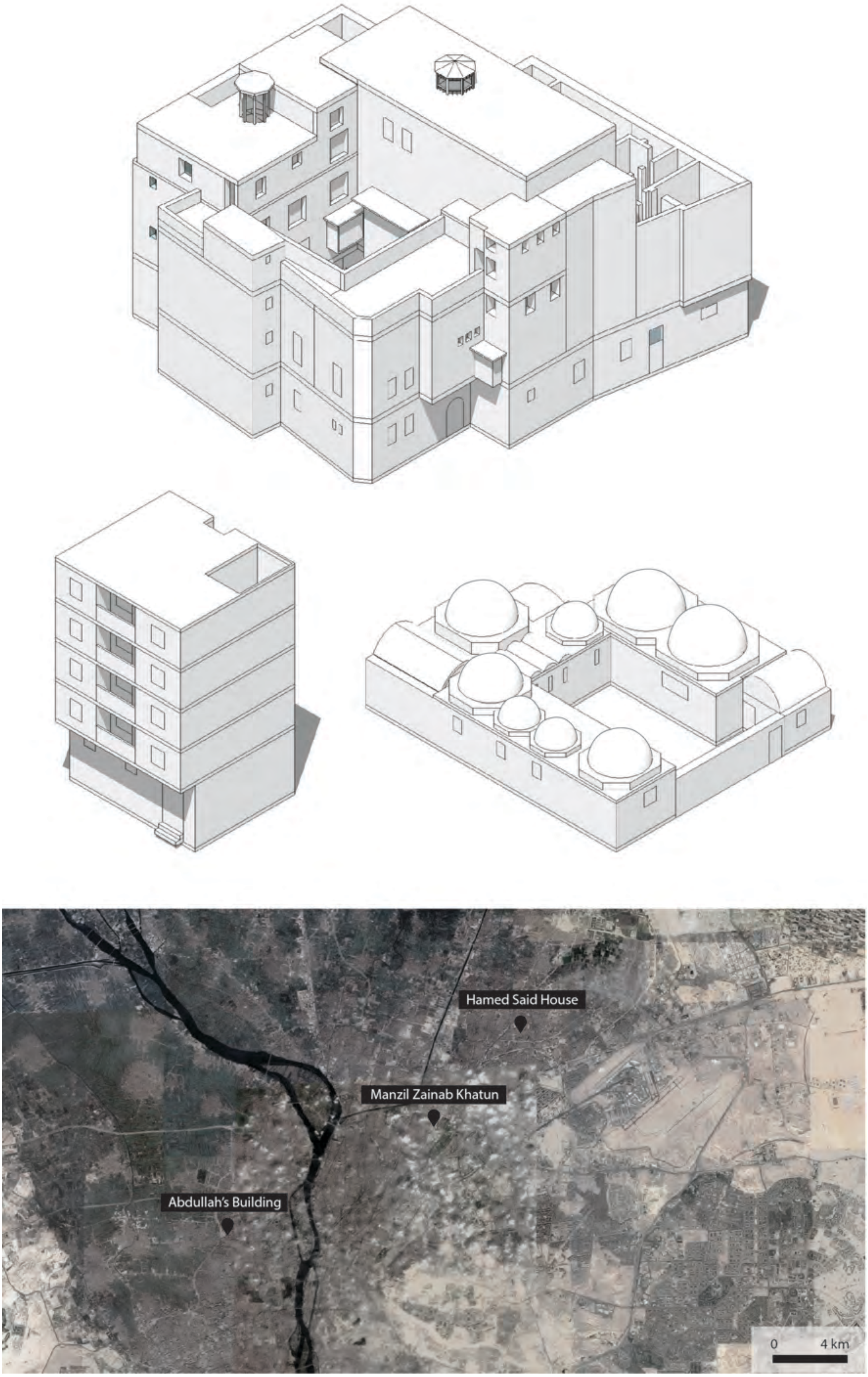


Figure 5.1 – The three typologies and their position: Manzil Zaynab Khatun (top), Abdullah's Building (center-left), Hamed Said House (center-right). Map adapted from Google Earth Pro (2018a).

This chapter applies *theoretical* and *empirical* methods to study three Cairenes dwellings built in different eras. While existing literature will give us an overview of the buildings' characteristics, qualities, and architectural vocabulary, tests done with Building Performance Simulation will help us assess their energy demands and thermal performance.

The buildings chosen for this research are *Manzil Zainab Khatun*, *Hamed Said House*, and *Abdullah's building* (see figure 5.1). Although an architect probably designed it, *Manzil Zainab Khatun* seems to put together all elements that constitute a vernacular building. It was designed and built in the XV Century by considering the climatic conditions and household needs, and it has been created using local knowledge, technologies, and materials. It is embedded in the core of historic Cairo, and it was built to mirror its culture.

Hamed Said House, completed by Hassan Fathy in 1945, is one of the manifestos towards a comeback to traditional architecture, built in a period in which modernism and internationalism were spreading globally. The small artist residence, built in the fields of what was considered the outskirt of the city, is probably the first dwelling built by Fathy in which most of the traditional vocabulary, learnings and strategies are adapted holistically to meet the needs of its users.

Abdullah's building, built around 2014, represents the informal typology of buildings described in the previous chapter. Behind its architectural concept, we might see many differences in comparison to the older buildings. It is a family-owned dwelling erected without the help of an architect and covers most of the needs of its occupants: it is a stable dwelling built by using local knowledge and resources, it can be expanded as the family grows, and the construction price makes it something feasible also for low- and middle-income families.

5.1. The Theoretical Approach: Observing Three Cairene Building Typologies

5.1.1. Manzil Zainab Khatun (Zaynab Ḫātūn, Zeinab Khatoon)

It does make sense to start this journey by looking at the oldest object used for this study. This will help us understand the vocabulary of vernacular buildings built before industrialisation. It will also give us a starting point for understanding the relationship of such a building with thermal comfort and energy demand.

5.1.1.1. History and Distribution of Spaces

The Zainab Khatun house - also known as Zaynab Ḫātūn or Zeinab Khatoon - is a beautiful home located in the centre of Historic Cairo, just some stones away from the Al-Azhar Mosque and the Al-Azhar University. Built in 1486 and with additions dated 1713, both the Mamluk and the Ottoman era have forged the house in what we can see today. Built on the remains of the residence of one of the granddaughters of Sultan Al- Nasir Hassan bin Qalawun -a Mamluk Sultan- it took the name of its last renowned owner (Garcin, Maury, Revault, & Mona, 1982; Jarrar, Riedlmayer, & Spurr, 1994).

Although in its current state it is incomplete – it might have included a stable, and the only remains of the Eastern side is a *hammam* without proper cover, and eventual upper floors – the reception rooms, the private apartments, the two *riwak* (central halls), a central courtyard, and the two-arches *maq'ad* (loggia), as well as the richness of its decoration and woodwork, testify the distinction and fortune of the former owner (Garcin et al., 1982).

As can be seen in other traditional Muslim houses, the shape and form of the Zaynab Khatun house have clear divisions between private, semi-public, and public space (see figures 5.2 – 5.5). The Islamic way of life defined what spaces were the domain of women (private and family areas) and men (public areas). A religious and cultural emphasis on visual privacy and the climate were the leading causes to develop buildings that were built introvertly. Family life took place in and around a central *sahn* (courtyard) instead of in the streets (El-Shorbagy, 2010).

Even though previously it might have been different, today, the *majaz* (entrance) of the house is in the South and is pointed out by a solid wood door embedded in a simple looking stone arch (Garcin et al., 1982). A typical element of this kind of house was the order of rooms and corridors that would lead the visitor to the courtyard. An essential function of this chicane was keeping the family's privacy – and that was also done by a doorman that would control, welcome, and introduce the visitors. Nevertheless, there is an added value about the architectural sequence of these spaces that cannot be ignored: the change of scale between the street and the dark entrance room, and the subsequent access to the courtyard, would only magnify the feelings of entering the house's core and showcase the family's "private piece of sky", as described in Arab cosmology (El-Shorbagy, 2010). Moreover, while entering the court, it is also possible to see the four – very different – facades in which *mashrabiya* –projecting windows with wooden lattice screens - and coloured screened glass windows witness the richness of its inhabitants once again. Besides functional spaces for the family's everyday life on the ground floor – such as storerooms, kitchen, a well and latrines - we can also find what is thought to be a men's meeting room and the men's reception. The latest is a representative room that, thanks to a big opening towards West, is overlooking the courtyard. From the yard, the rest of the rooms and upper floors can be accessed.

When looking at the only external staircase found in the court, one can only be impressed by the finely carved stone façade that invites and welcomes to the upper floor and another essential component of the Arab house: the *maq'ad*, an almost six meters high loggia with one double arch opening towards North and that overlooked the courtyard with its fountain and greenery. For the housemaster, the *maq'ad* was second in importance only to the *riwaq* – the great halls that can also be found on the same floor and accessed through a multifunctional room with *mashrabiya* or by the passage on the Northside (Garcin et al., 1982). While often such dwellings had only one *riwaq*, the Zainab Khatun house has a big one on the Eastside and a smaller one on the Northside. The great hall on the Eastern side has an area of about 100 m^2, and its height reaches almost twelve meters on its highest point. The great hall on the Northern side has an area of about 60 m^2, and its room height reaches six and a half meters. Both rooms – that might be described as majestic – have the same representative function and include common architectural elements. Each room has alcoves in which to sit, as well as *mashrabiya*. In addition, windows placed under the top of the room can be found, and both rooms have a central wooden lantern with openings (*shukhshakhah*) that allows the air to escape (El-Shorbagy, 2019).

The higher floor is where the private apartments and the roof terraces can be found. The rooms have a variable height that goes from 2,80 to about four meters, and while the lower rooms have only one window towards the courtyard, the higher ones have two windows placed one above the other. And while those rooms were not significantly different in the richness of details from the ones on the lower floors, it is in these rooms that latticework balconies and window grilles constitute the most luxurious and artistic element (Garcin et al., 1982).

Figure 5.2 – Manzil Zaynab Khatun – Ground floor and context.

Figure 5.3 – Manzil Zaynab Khatun – First floor and section West-East.

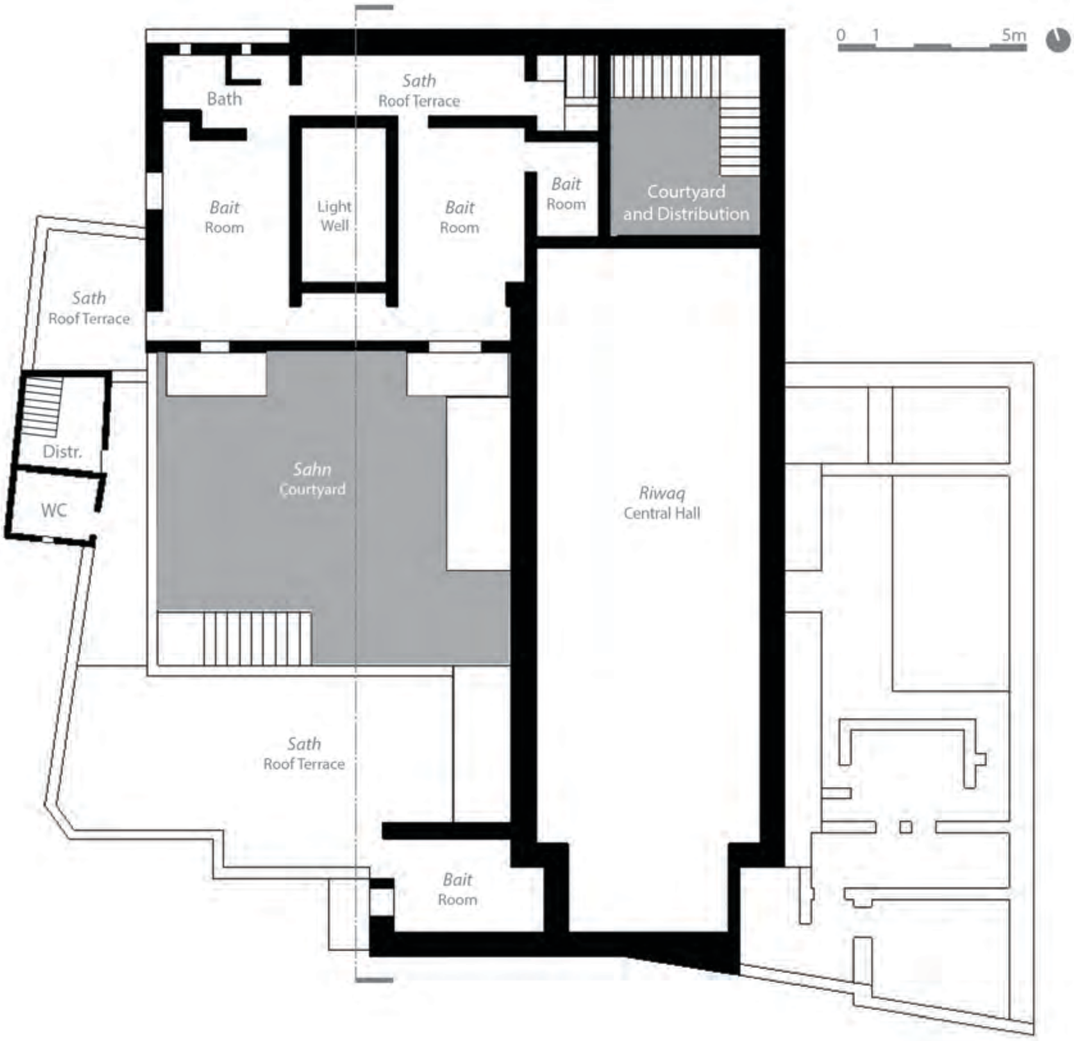
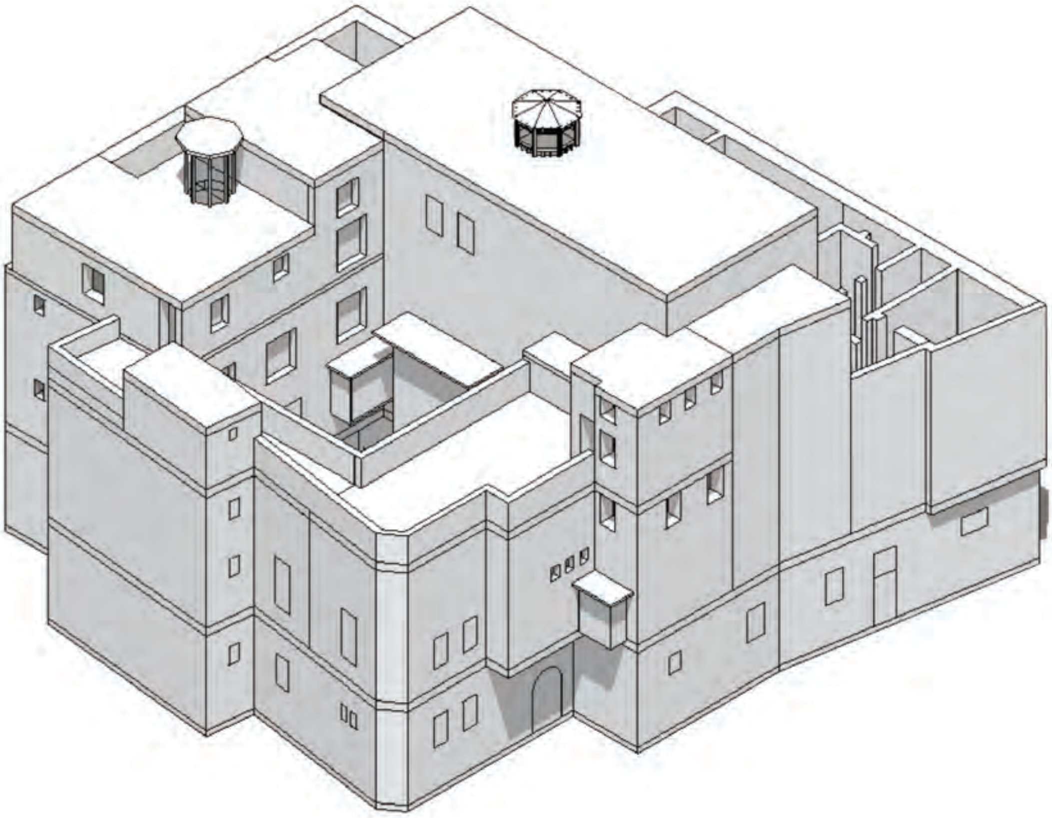


Figure 5.4 – Manzil Zaynab Khatun – Third floor and section North-South.



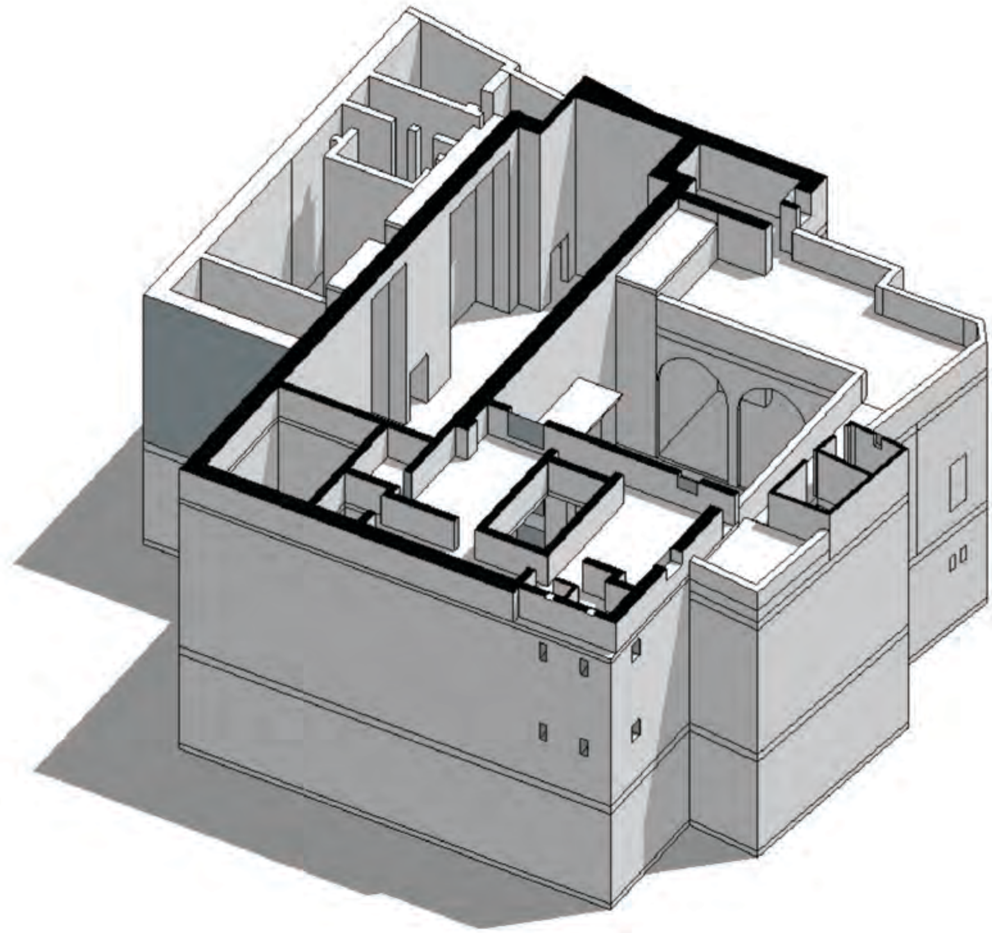


Figure 5.5 – Manzil Zaynab Khatun – Perspective and perspective with cut on the third floor.

5.1.1.2. Climate-Responsive Features and Comfort

To achieve thermal comfort, the most important things to keep in mind when designing a dwelling in a region characterised by a hot-dry climate are the reduction of solar heat gains (e.g. by shading façade and openings), and a having a good ventilation strategy that permits to remove the heat (Dietrich & Vignola, 2018a; Lavafpour, 2012; Vignola et al., 2019). By continuing our observations on the Zaynab Khatun house, we delve into the elements and strategies that are common to these kinds of vernacular dwelling, and that thanks to the local knowledge developed throughout the centuries have given its residents comfort holistically; the *sahn* (courtyard), the *mashrabiya*, the *maq'ad* (loggia), the s*hukhshakhah* (lantern), the materials used as well as the orientation of the rooms and the effects of sun and wind will be analysed in the following paragraphs[16].

The core of the house, the courtyard, while dating back to Graeco-Roman tradition (1900 B.C.), is probably the essential element found in Islamic-Arab homes. While suiting social, religious and privacy needs, it also provided solutions to environmental issues. The *sahn* offers natural light, protection from noise and dust, and enhances thermal comfort inside the dwelling (Abdelkader & Park, 2018; El-Shorbagy, 2010). The swinging temperatures between night and day and the fact that the courtyard and its four walls remain shaded for most of the day make possible the accumulation of night (cool) air distributed to the surrounding rooms and surfaces. When the court and its adjacent walls are heated by the sun during the day, the air moves by convection (stack effect) and permits the rooms to remain cool until late in the day (Fathy, 1986). Different studies have already shown the impact of a courtyard in mitigating the effects of a hot-dry climate (e.g. Aldawoud, 2008; Soflaei, Shokouhian, Abraveshdar, & Alipour, 2017; Soflaei, Shokouhian, & Soflaei, 2017). Wazeri, in a comparative study done in 2014 with three courtyard buildings in Cairo, has observed that the enclosure ratio, the walls height, and the façade projections have a significant effect in gaining the smallest amount of solar radiation. The study was also able to prove that the geometry of the Zaynab Khatun house is an excellent example of a well-designed space in this sense (Wazeri, 2014). Also, the detailed analysis and measurement taken by Mousa (2016) can confirm this. As in other traditional Arab houses, the central fountain and greenery placed in the *sahn* were of help in mitigating the temperature, adding moisture in the air, and improving the microclimate (see Attia, 2006).

As human beings, we need light, fresh air, and visual contact to the outside to feel comfortable in a closed space, and clearly, wall openings and windows can cover these needs. While in temperate climates all three functions of a window might be used simultaneously, in hot and dry climates, windows and openings might become a problem if not thought of well. The window position and their size influence the amount of air, light and radiation that enter a room. When looking at the plans and the pictures of the object of our investigation, we can observe that the facades towards the courtyard have a lot of openings with windows placed on the outer border. As we have seen in the previous paragraph, this makes sense because when the sun is stronger in summer, the sun position is higher, and these windows get very few direct radiations. On the other

[16] The reader wanting to dig more into the different features will find interesting the following publications that focus on Arab traditional dwellings and the ones found in Cairo: Ragette, F. (2012). *Traditional Domestic Architecture of the Arab Region* and Garcin, J.-C., Maury, B., Revault, J., & Mona, Z. (1982). *Palais et maisons du Caire - I Époque Mamelouke (XVI - XVIII siecle)*.

hand, in the facades towards the streets, there are few openings with the windows placed toward the inside of the room. By doing so, the thick wall acts as an overhang during the warm hours of the day, keeping the external sun gains away.

Although it can also be found in other hot-dry regions (in Asia, North and East Africa, and Europe), an important element of Arab houses is the *mashrabiya*. As explained by Fathy, "the name is derived from the Arabic word *drink* and originally meant *a drinking place*… it was a cantilevered space with a lattice opening, where small water jars were placed to be cooled by evaporation effect" (Fathy, 1986, pp. 46, 47). Over the years, the *mashrabiya* has changed in form and function, and sometimes it can be found as a wooden lattice screen set into the façade. Its functions are manifold: it controls the passage of light and airflow, reduces the temperature of the air current, helps in increasing the internal humidity, and it ensures privacy (Ashour, 2018; Fathy, 1986). Added to that, the artisanal fine woodwork would also give an added aesthetic value to the façade. In the Zainab Khatun house, it is possible to see two cantilevered *mashrabiya* integrated into the Northern *riwaq*, one in the Easter *riwaq* and one behind the *maq'ad.* Examples of *mashrabiya* set directly into the façade can be found in the Northern *riwaq* and the upper apartment (again, used as a latticework balcony). Except for the small *mashrabiya* overlooking the street and the entrance, the other ones overlook the courtyard.

Another strategically used device in both central halls (*riwaq*) coping with the *mashrabiya* is the *shukhshakhah* (skylight, lantern) placed on the top of the high room's roof. The air circulates from the courtyard through the *mashrabiya* and the lower openings and finds its way out through the wooden lantern. Here again, air circulation is made possible by the convection created by the heated roof of the lantern and the flat building roof (El-Shorbagy, 2019). Also, because lower windows are absent, the house's central hall is considered the best-equipped room to withstand the external heat, making it the most pleasant room in any season. In summer, the paving in stones and polychromatic marble would help the feeling of coolness through convection. In winter, warm woollen rugs were spread on the floor for achieving the opposite effect. In some similar dwellings (e.g. *Bayt el-Suhami)*, a fountain can be found beneath the skylight to improve the microclimate in summer. The same feature was used in colder months to heat the room by filling it with hot coal. (Garcin et al., 1982; Jarrar et al., 1994). Although not present in the Zaynab Khatun house, another device found in this kind of house that helps improve air circulation is the *malqaf* (wind catcher). This is a shaft with one open side that rises above the building. It can catch the prevailing wind (in Cairo, coming from the North) and channel it towards the house's interior (Abdelkader & Park, 2018; Fathy, 1986). The prevailing wind was also the reason behind the position of the *maq'ad* (loggia). This elegant and high room, placed on the first floor and directly accessible from the courtyard, was used by the residents and their guests during the day's cooler hours or the season. The view towards the courtyard, with its greenery and water features, would certainly also enhance a relaxing experience that would let forget for a while the hustle and bustle of the city (Garcin et al., 1982). The breeze coming from the courtyard would enter the large open façade and continue towards a small opening on the top of the Southern wall and the other internal rooms.

The right choice of construction materials is one of the last pieces of the puzzle to create a climate-responsive building in which all strategies mentioned above can support each other's, and lastly, comfort its dwellers. Just as it happened in the days of Pharaonic Egypt, resources such as clay, limestone, plaster, lime, sand, and some sorts of wood were abundant in the Nile Valley, the desert and the Mukattam mountains. Therefore, most of the resources used for construction could be found in and around Cairo. In addition to the regional marble, the marble from Aswan was imported via the waterway from Upper Egypt. Only complementary materials were imported from nearby countries, such as resistant wood to be used for wood structures such as ceilings or carpentry work and cabinetry (Garcin et al., 1982). What can be observed in the Zaynab Khatun house is that the bearing walls of the ground floor are made of clean-cut stones (about 65 cm of limestone). The upper floors and latest additions have walls of 30 to 65 cm built in burnt bricks (Centre for Conservation & Preservation of Islamic Architectural Heritage, 2021; Garcin et al., 1982). Although the dwelling has ornamental wood elements to cover part of the *riwaq's* walls and ceilings, the use of plaster with the addition of sand can be seen on every internal wall. Most of the external walls have no plaster coating – exception being the two central hall walls that look towards the courtyard. Generally, the paving of all internal spaces is made in limestone slabs placed on one layer of sand and one of mortar (plaster and sand) that are sustained either by a frame ceiling or a masonry vault. The same can be said for the terraces on the roof, although we assume that for the top layer of all non-accessible roofs, instead of cut stones, mud has been used (Garcin et al., 1982; Ragette, 2012).

Besides being locally available, those materials and constructions were also chosen because of their physical properties (thermal conductivity, resistivity and transmission, reflectivity, etc.). Through time and by gaining knowledge on a trial-and-error basis, these skilful constructors had understood what kind of construction and material thickness was adequate to maintain constant and comfortable temperatures throughout the year in the specific Cairene climate. In hot and dry climates, by using constructions with high heat-absorbing capacity materials, inside temperatures are kept more constant than by using ones with a low one. During summer, while the structure would remain cool until the early afternoon, thanks to lower night temperatures, the heat coming from outside would start affecting internal temperatures only later in the evening (E. O. M. Raslan, 2016). In chapter three, we saw already this phenomenon while comparing brick and adobe construction (see figure 3.5). As already commented by other researchers, other factors that are relevant for the spatial organisation of spaces in a Cairene dwelling are the sun path and the wind direction; the best orientation in regards to the sun is East-West, while according to prevailing winds, is North-South (Abdelkader & Park, 2018; Fathy, 1986; Lavafpour & Surat, 2011) In the case of Manzil Zaynab Khatun, we have already seen that the *maq'ad* is positioned by following the North-South wind path. Thinking about the general layout of the habitation, we can speculate that, including the parts of the house that have not made it until our days, it followed the East-West orientation. This would have also been keeping the main central hall more embedded in the construction – and therefore keeping distant the direct heat gains due to the morning sun from the walls that are nowadays exposed (Garcin et al., 1982, pp. 195–196).

In the last couple of pages, we overviewed the characteristics of a typical urban Arab dwelling built during the Mamluk times. Its vocabulary is rich in elements connected both with the social and religious customs of that time. Thanks to the materials and technologies used and local knowledge, it is adapted and responds well to the Egyptian climate conditions. In the following pages, we are going to analyse another building, that even though it was built less than eighty years ago, took inspiration from vernacular traditions that – in contrast to the Manzil Zaynab Khatun – comes from a more rural tradition, the one coming from the people of the desert: the Nubians.

5.1.2. Hamed Said House

While the previously analysed dwelling was indeed meant to address the needs and customs of their owners, such houses were built by wealthier and more-than-average folks. The Hamed Said house was built with quite a different approach: proving that it is possible to construct a dwelling using traditional techniques that can also fulfil humble end-user's needs while being climate responsive. Here we will see how that would be possible, and, again, by digging in the architectural vocabulary used, we will see how design choices might impact the well-being of its dwellers within this climate.

5.1.2.1. History and Distribution of Spaces

Hamed Said and his wife Ehsan Khalil, close friends of Hassan Fathy, were both artists who lived in the Mukattam Hill in Cairo. While they had to find a new accommodation – their house had to be destroyed to make place for a highway - they were offered a piece of land for a new studio in Marg, a village in the outskirt of the city. And there, partly because of their economic situation and partly because they loved to live near nature, they lived in a tent. It is said that before starting the formal design process, Fathy used to stay with Said and Khalil in the tent to gain a better understanding of the area and its character (El-Shorbagy, 2019). In any case, who, better than its architect, could give us an idea of how the Hamed Said project started?

> *Just outside Cairo, in Marg, lived another friend of mine, Hamed Said. He was an artist and lived with his wife in a tent, partly to be near nature, which he greatly loved, partly because he could not afford a house. When he heard of the Royal Society of Agriculture farm at Bahtim and how little it had cost to build, he grew most interested, for he had wanted a studio for some time. He went to look at the buildings, and when he saw the unique quality of the light in a vaulted loggia there, he immediately decided to build a similar loggia for himself. Some relatives of his had a farm, on which we put up a studio consisting of one large domed room, with a vaulted bed alcove, built-in cupboards, and an open-ended loggia giving onto the fields and an uninterrupted view of acre after acre of palm trees. He had the bricks made on the spot—the soil was sandy, so he didn't need even straw—and the masons built the house for just L.E. 25. We picked up some very beautiful old wooden grilles for the windows and some cast-off doors for the cupboards, all long since discarded in favor of shiny European-style fittings.* (Fathy, 1978, p. 6).

Between the lines, we can recognise some of the characteristics of Fathy's philosophy. Around the time the house was built, the Cairene intellectual community was concerned about the adverse effects of industrialisation on traditional cultures, and therefore was looking for answers within the Egyptian tradition. Fathy, Said and Wassef (another Egyptian architect), together with a group that included artists and philosophers, promoted not only the natural environment and the use of resources and knowledge available in loco, but also "group effort" – work produced by human hands that relates inspiration, integrity, and unity of a group instead of an individual – which in their eyes was contraposed to the "dehumanising mechanisation" of modernism (Steele, 1989). Furthermore, both Fathy and Said, going against the standardisation brought up by the modern movement, believed that an architect should translate into architecture the requirements and needs of the end-users, therefore creating something unique and appropriate for each person (El-Shorbagy, 2019).

Although in its subsequent projects Fathy has been able to employ the traditional vocabulary in a more extensive way – such as in the New Gourna village, started in 1945 -, Hamed Said house is considered Fathy's starting point to test solutions coming from the Nubian tradition (El-Shorbagy, 2001, 2019). From the use of materials and ancient crafts to the use of spatial and constructive elements such as the courtyard, the thick walls (either in stone or mud-brick) with small openings, vaults and domes, the Nubians have been master builders since the dawn of time. Both at the building and the urban scale, Nubian architecture has demonstrated being able to adapt to its environment, to the social and cultural changes happening during many centuries, and be economically feasible thanks to the locally available materials (Mahmoud Bayoumi, 2018; Sayigh, 2019). Although there is also a considerable number of dome roofs in this building (that traditionally were primarily used for monumental and funerary architecture by the Nubians), in the Hamid Said house, we can also appreciate a good number of Nubian vaults – something that made a mark on Fathy's architecture. The value that this kind of construction has had for Fathy can be understood by reading what he has written in *Architecture for the poor*:

> *Soon afterwards, the war started, and all construction works stopped. Steel and timber supplies were completely cut off, and the army requisitioned the materials already in the country. Yet, still obsessed by my desire to build in the country, I looked about for ways of getting around the shortage. At least I still had mud bricks! And then it occurred to me that, if I had mud bricks and nothing else, I was no worse off than my forefathers. […]*
>
> *I could build walls, too, but I had nothing to roof them with. Couldn't mud bricks be used to cover my houses on top? What about some sort of vault? Normally, to roof a room with a vault, the mason will get a carpenter to make a strong wooden centering which has to be removed when the vault is made; this is a complete wooden vault, running the full length of the room, held up by wooden props, and on which the courses of the masonry vault will rest while being laid. But besides being elaborate and requiring special skill to insure that the voussoirs are pointing toward the center of the curve, this method of construction is beyond the means of peasants.*
>
> *[...]*
>
> *My elder brother happened at that time to be a director working on the Aswan Dam. He heard of my failure, listened sympathetically, and then remarked that the Nubians were, in fact, building vaults that stood up during construction without using any support at all, to roof their houses and mosques. I was immensely excited; perhaps, after all, the ancients had not taken their secret to their provoking vaulted tombs with them. Perhaps the answer to all my problems, the technique that would at last let me use the mud brick for every part of a house, was awaiting me in Nubia* (Fathy, 1978, p. 3).

We can only assume that the limits imposed by the available resources made the Nubians master the vault by stacking bricks at a slight angle and resting them against a wall. In any case, we are confident that this ancient tradition helped solve a "modern" constructional problem that would come up in times when resources were scarce. [17] (Asquith & Vellinga, 2006).

[17] For the reader interested in the technical aspects of a Nubian vault, see: *The architecture of Hassan Fathy: between western and non-western perspectives* (El-Shorbagy, 2001)

Hamed Said house was built in two phases (see figure 5.6). The first phase occurred in 1942 and included what Fathy described above – one open-ended loggia on the Westside, one central domed room to be used as a studio, and one vaulted bed alcove on the Eastside. The second phase, finished in 1945, was designed as a continuation of the existing spaces. A vaulted gallery facing South was added. On the eastern and the western sides, two wings connected to the gallery were added and thank to a massive wall built between the two south wings' facades, a courtyard was created. In the East wing, two connected domed rooms were used as the artists' studio, and the porter (doorman) used a smaller vaulted room. In the West wing, a bedroom, a bathroom, a kitchen, and a living room can be found – all of them under roof domes.

5.1.2.2. Climate Responsive Features and Comfort

By looking at the different elements and principles that make this kind of building climate-responsive, we recognise some similarities between the Hamid Said house and the Manzil Zaynab Khatun. Starting with the courtyard, also in this case is to be considered the place in which most of the "public" life of the family took place. It had trees, palms, and greenery that would help improve the microclimate and give shadow to the space and its facades.

Sixty centimetres thick walls made with a double layer made of mud bricks, the small openings (with *mashrabiya* set into the façade) and the vaulted or dome roofs create a system in which the internal climate would comfort its inhabitants all year long. The sun-dried bricks have proven to work best both in that climate, improving heat accumulation capacity, and also to be the excellent construction material to reach appreciable heights over small surfaces (Al-Ajmi, Abdalla, Abdelghaffar, & Almatawah, 2016; Arsenovic, Lalic, & Radojevic, 2010; De Filippi, 2006; El Fgaier, Lafhaj, Brachelet, Antczak, & Chapiseau, 2015). Traditionally, palm ribs and leaves were used together with mud, acacia, and palm wood for the plain roofs. Interior finishes that might have had a painted limewash coating were made with a fine earth mortar render. On the outer surface, mud and straw plastering was used: it protects brickworks, it is a permeable material that allows the walls to breathe and can be renovated whenever needed. Furthermore, its light colour reflects the solar radiation while blending nicely with the landscape (De Filippi, 2006; The Nubian Vault Association, 2015). Although the Nubians used compressed earth for the paving, pictures of the Hamed Said house show that probably here limestone slabs have been used[18].

As already seen in the Manzil Zaynab Khatun, also in this dwelling, the concept of stack ventilation has been cleverly used. Although most rooms are not bigger than twelve square meters, their height varies between 4,70 meters and almost eight meters. The roofs, which include small openings in the dome, permit hot air to exit the rooms. This effect is amplified by aligning windows (positioned at eyes height) and doors from outside to inside, allowing cross ventilation in most rooms.

And that brings us to the orientation of the building. It was impossible to find information about it; we assume that the plans have been drawn with the typical architectural standard. When no North arrow is found, the upper side of the drawing is oriented towards North. Different clues can support this assumption. First, when looking at what has been built in the first phase, we can notice that the shorter sides of the building would face West and East. This, to minimise direct

[18] See egyptarch.net – Hammed Said (accessed 01.07.2021)

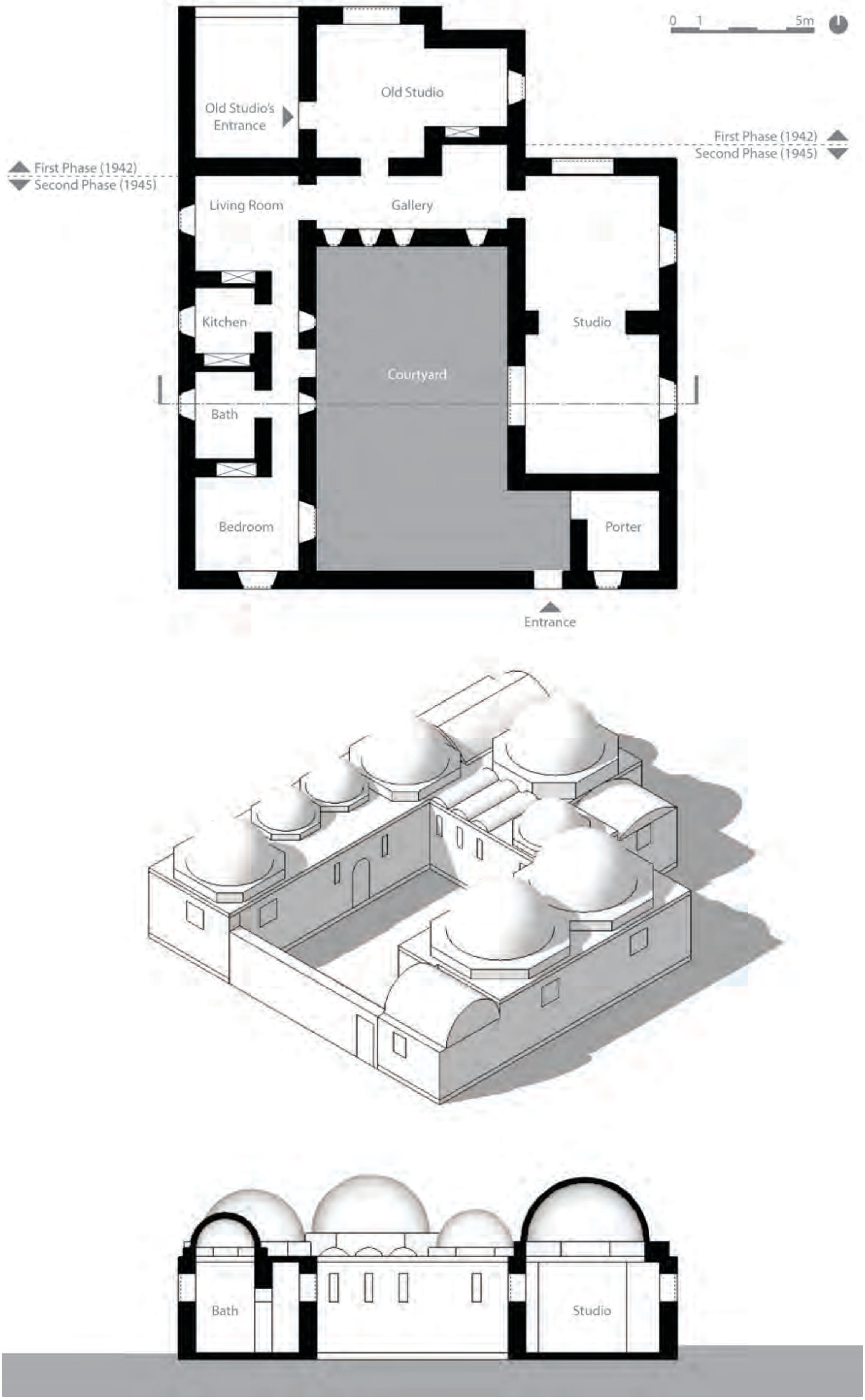


Figure 5.6 – Hamed Said House – Plan, perspective, and section West-East.

sun radiation during the summer months. Furthermore, observing the big openings under the vault and in the studio would be placed towards the North to catch the wind. And this is precisely what we have already seen when analysing Manzil Zaynab Khatun. Second, by observing the pictures of the building, and focusing on the shadows of walls and plants, although we do not have information about the period of the year or time in which the pictures were taken, we see a lot of similarities to the shadows simulated by using SketchUp. Even though the area of walls towards East and West increased considerably with the second phase, we should not forget that when Hamed Said house was built, it was embedded in a field full of trees and greenery. [19]. By doing this, it was possible to keep most of the walls shaded.

After having observed the principles and features that support Hamid Said house's architecture, we see a rural home in which features coming from the desert architecture of the Nubians have been newly interpreted to cover the needs of its users. With the knowledge gained, it is possible to say that such construction has shown its economic feasibility while considering both the climate constraints and the habits and the comfort of its dwellers.

Finally, within the following pages, we will go through the features of a building that represents most of the buildings built during the last seventy years in the Egyptian Capital: Abdullah's building, a multi-storey house built recently within an informal framework and dictated by rules that apparently have nothing to share with the vernacular features observed in the previous house typologies.

5.1.3. Abdullah's Building

As we have already discussed in chapter 04, although a recent phenomenon, informal buildings are the type of buildings in which most Cairenes live. The brick-and-concrete construction characterises the dominant typology of such buildings, just like the one of Abdullah, built probably in the second decade of this century. By describing its characteristics, we will encounter many of the features expected in such dwellings. Furthermore, adding to the learnings from the previous examples, we will understand why this typology is so popular. Focusing on the thermal comfort of its dwellers, we will dive into the advantages and drawbacks of such construction.

5.1.3.1. History and Distribution of Spaces

The building is located in the very densely populated Ard-el-Lewa and is erected on an area as big as a half *qirat* - the smallest *feddan*[20] subdivision available (10 meters by 8). By looking at historical satellite images[21], it is possible to observe that the patch of land, still used for agriculture until the early 2000s, had become one of the latest areas in which to build in the vicinity of the city centre – and at one-fifth of the rent price of the Mohandessin area in Giza (see also figure 4.5), just on the opposite side of the railroad. Although with some uncertainty, we might assume that Abdullah's building was built between 2010 and 2015. In the meantime, the green patch of land has left the place to unplanned buildings that, by also growing in height – several towers have been built lately – have increased the building and resident density even more.

[19] See, e.g. the pictures that were taken in 1973 by John Norton: https://dwarchive.com/archive/house-hamed-said-1, https://dwarchive.com/archive/house-hamed-said-0 (accessed 01.07.2021)

[20] One *feddan* is equal to 4200 m^2 (World Bank, 2001), one *qirat* is equal to 175 m^2 (Sims, 2012, p. 173)

[21] See, e.g. the satellite images on Google Earth with the dates 11.2000; 05.2003; 06.2009 and 11.2015 (30° 3'2.29"N; 31°10'57.59"E)

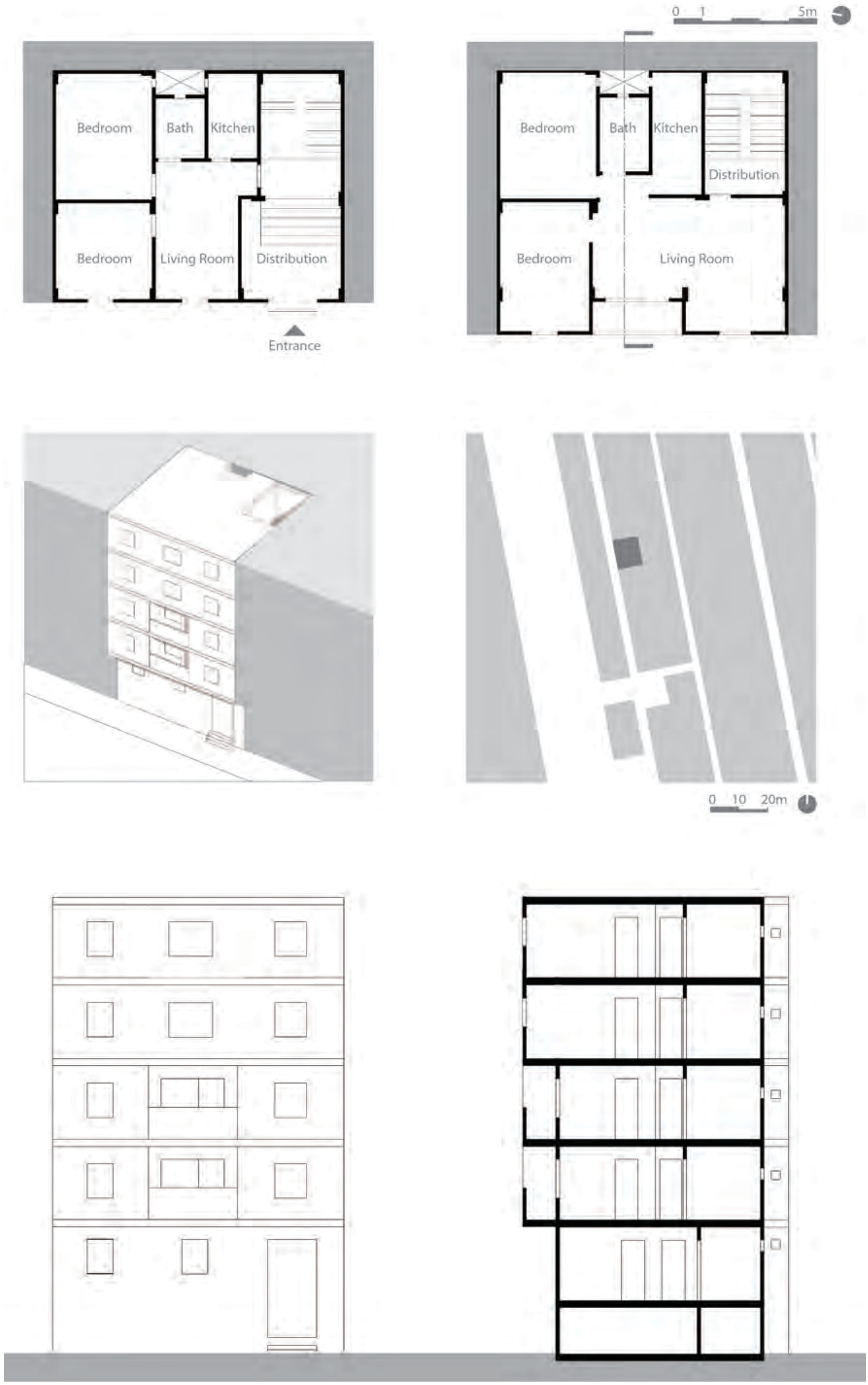


Figure 5.7 – Abdullah's Building – Ground floor, typical floor, perspective, context, elevation West, section West-East.

Abdullah's building is family-owned, and with the three blind facades, one façade facing the street, its elevated ground floor, an apartment per floor, a single corner staircase, a small ventilation shack, an unfinished rooftop (for future vertical expansions), represents a very common typology in the area (Angelil et al., 2016, p. 135; Sims, 2012). Nevertheless, generally speaking, the apartments have lost most of the features seen in Mamluk and Nubian architecture (such as the spaces separated by gender, the courtyard, the high ceiling, etc.) and, by dividing the spaces efficiently and economically, they mirror a building culture that can also be found in other world's metropolis.

As shown in figure 5.7, while many informal buildings include some sorts of commercial activities on the ground level, Abdullah and his wife live on this floor in 55 square meters. On this floor, the entrance and distribution shaft takes up about one-third of the area. The living room and one bedroom have windows facing West and the street. The other bedroom, the bathroom and the kitchen face East, and small windows are located in the shaft, which measures less than two square meters. The upper floors, destined to Abdullah's sons and daughter families, adject one and a half meters towards the street, have an almost identical layout and measure about 75 square meters. The program of the upper apartments is very similar to the one on the ground floor, but thanks to the adjecting West wall and full use of the floor, both the bedroom and the living room gain some square meters. A large window has substituted the terraces on the first and second floors on the third and fourth floors.

When observing the spatial distribution of Abdullah's building surface, we can see that besides the space used for living, the entrance and staircase occupy about 14 per cent of the building's area. In contrast, the shafts occupy only 1,5 per cent. The other buildings analysed by Angelil et al. ranged between 5,1 and 5,6 for the distribution, and the percentage of the area dedicated to shafts varies from 2,8 to 7,5 per cent (2016, p. 132,133).

5.1.3.2. Climate Responsive Features and Comfort

Let's look back at the experiment illustrated in chapter 3 (3.4.1 - Projected Performance of Two Rooms in the Greater Cairo Region). We might remember that the model built with adobe performed better than the construction done in concrete and burnt bricks.[22]Suppose informal buildings were judged only by observing the materials used and by seeing how economically driven the construction goes. In that case, one might say that there is no probability for calling such buildings *climate responsive*. Delving a bit more into Abdullah's building will help us to understand how both the structure and its built context create a system that, although it might have some drawbacks, might also be well suited for the Cairene hot and dry climate.

The first informal buildings were single-family houses (called *bayt*) with one or two stories built using techniques and materials found primarily in Egyptian rural architecture. Wall bearing structures with dried mud bricks were not uncommon. Slowly, also thanks to the workers coming back from the Gulf in the seventies, those typologies developed further in what we know today as "classic informal"; three to six-story buildings with reinforced concrete and beam structure with brick-wall infills (Angelil et al., 2016, p. 85). By looking at the analysis done by Ostrowsky & Zerlauth we can have already have a first sneak peek into the economy of the materials used. The long section of the concrete columns loses ten centimetres every two stories, while the infill

[22] Yearly comfort hours were fulfilled 89,0 % with the adobe model and 79,6 % for the bricks model (EN 15251, comfort class II; weather data: 1990).

walls have a section of a single burnt brick of about twelve centimetres – just like the internal partitions. Thin reinforced concrete floor slabs are covered with a layer of sand and stone paving, and the roof slabs remain "naked" until the building has got all vertical extensions needed. In this kind of dwelling, plaster is used only for internal finishing, while on the external façade, both the concrete structure and the brick infills remain visible. The use of mud-bricks was banned during the nineties for environmental reasons. Nevertheless, burnt-brick factories and workshops can be found in Cairo and Giza, making this one of the most available and cheapest construction materials (see *Snapshot of construction*, in Angelil et al., 2016, pp. 88–97).

As it is custom, with a window/floor ratio of about nine per cent, the openings on the façade facing the street are big enough to let some light pass but small enough to block external gains; Venetian blinds can be found on buildings that have direct solar gains exposure. Probably, because of the building's orientation and the fact that the opposite construction keeps the main façade shaded, shading systems can be found in Abdullah's building only partially. The openings towards the shaft are small and mainly used for ventilation and odour extraction.

The shaft is probably the most common internal feature in this kind of buildings. Although nowadays we might consider a courtyard space-consuming, in older times, it was considered a multifunctional element in which the representation of richness was measured while improving the microclimate and offering privacy. This element has been transforming decade after decade. As the nineteenth-century buildings in Cairo Downtown proof, evolved into an internal and spacious space in which vertical distribution and air exchange are possible. Later, with land pressure becoming more and more present, this feature adjusted in size, becoming an element with the sole scope of providing natural ventilation and light without accessibility (Angelil et al., 2016, p. 78). As we can observe by looking at the plan of the building, even though a shaft is present and it is cleverly placed (offering an opening to three rooms), because of the windows position and the internal walls, cross ventilation might not be possible. This assumption is supported by what was written by Kipper & Fischer when they observed that by taking into consideration the narrow access towards the street, these buildings are often poorly ventilated and lack natural light (2009). So, how do informal dwellers find comfort when internal temperatures increase over the comfort zone? Most rooms are equipped with ceiling fans, while a small percentage cool down essential rooms with air-conditioning units.[23] (Sustainable Building Conference Cairo 2013, 2013; U.N. Habitat, 2011).

We should not forget that just like Abdullah's building, most informal structures are embedded in a very dense context that permits them to receive solar radiation and direct heat gains only through the roof and the highest floors. The materials used for the structure will never have the same heat capacity as those shown in the previous two examples. Nevertheless, if we think about the perimetral walls of the blind facades, the heat capacity will be higher than the one of single-layer bricks due to the external walls of the adjacent buildings. As we did in the other examples, we need to spend a few words about the building orientation to complete this short analysis. We have already seen that to reduce solar gains, an East-West orientation would be the favourite, and for catching the summer breeze, the Northside of a building should be the one with more access

[23] Although quantitative research would be needed to have a representative outcome, observations done by the author in 2017 and 2018 in an informal settlement in Cairo (al-Matariya), that only about five per cent of dwellings had an external Air Conditioning unit.

to the wind. In the case of Abdullah's building, the long side of the building has a North-South orientation, and the only visible façade faces West. Hence, while there might be no access to direct wind, the solar radiation coming in the afternoon and evening are blocked by the opposite building. By looking again at aerial views of informal settlements, we can observe that the groups of building blocks follow regular patterns with different orientations while being quite orderly. These patterns come from the old agricultural land subdivisions, divided into strips of land (six to seventeen meters wide and 100-300 meters long) framed by irrigation canals. Therefore, while having streets delineating the old fields' structure, the small lanes are placed where once irrigational channels used to be (Malterre-Barthes, 2016; Sims, 2012, pp. 112–113).

As we have seen, although we can imagine that it might be challenging to achieve thermal comfort in Abdullah’s building during the whole year, some clues lead us to think that the situation might not be as bad as generally thought. On the one hand, the limited use of material, and therefore, the (apparent) low heat capacity of the building, might let fluctuate the internal temperature more than in the other analysed buildings, and high temperatures might be achieved in summer – especially in the upper floors. On the other hand, thanks to a small window to surface ratio, and the fact that the dwelling is embedded in a dense context, sun gains are blocked most of the time. Added to that, the flexibility of building floor after floor (when economic resources are available) and using local workforce and materials makes these multi-storeys dwellings unbeatable when thinking about the socio-economic condition of most of Cairenes. As described by Oliver, "these structures are, indeed, the closest equivalent to contemporary Egyptian vernacular” (1997b, p. 1604).

5.1.4. Strategies and Systems for Enhancing Thermal Comfort

The three analysed buildings were built in different centuries and have been able to respond to the needs of their occupants while being embedded in different socio-economic contexts. As we have seen previously, different systems and features have been used strategically to let the inhabitants of these dwellings be - within their possibilities - comfortable in the Cairene hot and dry climate. By adapting the work done by Roaf et al. (2005), Lavafpour (2012), Farouh and Amer (2018), both the systems and the strategies used in the three buildings are summarised in table 5.1. With strategy, we intend the architectural principles and design criteria which for a feature or a system is implemented in this kind of climate: minimise solar gains and conductive heat flow, interception of solar gains, promote ventilation, radiant cooling, earth cooling and evaporation (Lavafpour, 2012). (A *mashrabiya*, for example, is in this sense an external shading system strategically built to intercept solar gains.) At first look, it might seem clear that Manzil Zaynab Khatun has more features than the other buildings to respond to the climate. Nevertheless, some points can be discussed further.

For minimising solar gains and conductive heat flows, all building designs include compact volumes with small windows. An insulated roof is missing on all three buildings, while the orientation of the building and having a high thermal mass has been considered in the two older typologies. The informal building was built by following the old agricultural land boundaries. Therefore the orientation was given. Nevertheless, it might have a higher thermal mass when considering the adjacent buildings. The interception of solar gains is done differently depending on the possibilities and space at disposal. An external shade of openings can be found in the older buildings (mashrabiya, thick walls with windows placed towards the inside) and partially, also shutters. In Abdullah’s building, external shading features were not implemented, and shutters appear only on some windows (in other informal buildings they might be present). When digging into the different elements used to shade, Manzil Zaynab Khatun has a distribution volume on the Westside and greenery that shade the courtyard during the afternoon. Hamed Said house, being built as a standalone house on a field, has trees and plants inside the courtyard and all around the house perimeter. Added to effects given by shading the building, plants also promote evaporation, and therefore an improved microclimate. In a very dense context, Abdullah's house has three adjacent buildings and one opposite to its main façade that intercepts solar gains. In all three buildings, solar gains are partially reflected thanks to the light coated rooftops. To promote radiant cooling only in the older typologies, we can find a courtyard. Due to the imposing size of the house, only Zaynab Khatun house has rooms placed and oriented differently, in which their inhabitant could adapt and use it at specific times of the year (or the day).

By delving into the design strategies to promote ventilation, we can notice that only the ventilation shaft has been used as a feature in Abdullah's building besides the small windows. To generalise, orienting this building towards the prevailing wind and enabling cross-ventilation might be possible in the proper context. At the same time, looking at features such as verandas, wind catchers, earth cooling, and high rooms (to permit stack warming and cooling) might be difficult due to the economical use of space. The other two buildings have been designed to use the wind by positioning the veranda towards the North and the openings (including windows and doors) to enhance cross-ventilation. Even though without including a wind catcher or an earth cooling device, the high rooms of Manzil Zaynab Khatun, also thanks to the lantern cleverly positioned, allow for stack cooling and warming. The house designed by Fathy, being only one storey high, makes use of the stack effect thanks to the high rooms covered with domes and vaults.

On the one hand, when observing the features related to cutting or reducing solar gains, every building responds to it by using what was at its disposal when they were built – being a design decision or the use of the context. On the other hand, when looking at ventilation strategies, we can notice that, while in the older typologies, different systems have been implemented for promoting ventilation, in the informal ones are very limited.

Within this theoretical part of the work, we have been able to get a first idea about the three buildings. This, by delving into their history, the strategies used to comfort their occupants and understand their architectural vocabulary. In the following pages, we will delve into the empirical study that will help us assess the thermal performance of the buildings and their energy demands.

5.2. The Empirical Approach: Performance of Three Cairene Building Typologies

This empirical part aims to assess the thermal and energy performance of the three buildings and confirm (or reject) the observation described in the last part of the work. The following paragraphs describe the methodology used for testing digital models of the three buildings with a Building Performance Simulation Software. All primary inputs, differences between the models, as well as the expected results, are summarised. In the subchapter *results and observations*, the outcomes of the tests (thermal performance, heat, and cooling demand of the buildings, sensitivity analysis) are reported, visualised and discussed. In the final part of this chapter, the results are summarised.

Table 5.1 – Passive systems and design strategies found in the three analysed buildings. Adapted from Roaf et al. (2005, p. 201).

RANGE OF ADAPTIVE OPPORTUNITIES AVAILABLE TO BUILDING USERS TO AMELIORATE THE INTERNAL CLIMATE USING PASSIVE SYSTEMS IN HOT AND DRY CLIMATE				
Passive System	**Design Strategy**	**Manzil Zaynab Khatun**	**Hamed Said House**	**Abdullah's Building**
Solar Orientation	Minimize Solar Gains	●	●	-
Compact Volume	Minimize Solar Gains	●	●	●
Small windows	Minimize Solar Gains	●	●	●
Insulated Roof	Minimize Solar Gains / Minimize Conductive Heat Flow	-	-	-
Thermal Mass	Minimize Conductive Heat Flow	●	●	○
External Shade (e.g. , Mashrabiya, Overhang)	Interception of Solar Gains	○	○	○
Shading by Agglomerate of Volumes	Interception of Solar Gains	●	-	●
Shaded from West Sun	Interception of Solar Gains	●	-	●
Shutters	Interception of Solar Gains	○	○	○
Planting	Interception of Solar Gains / Promote Evaporation	●	●	-
Wind Orientation	Promote Ventilation	●	●	-
Verandas/Colonnades	Promote Ventilation	●	●	-
Cross-Ventilation	Promote Ventilation	●	●	-
Stack Cooling	Promote Ventilation	●	●	-
Stack Warming	Promote Ventilation	●	-	-
Lantern / Ventilation Ducts	Promote Ventilation	●	-	●
Wind Catcher	Promote Ventilation	-	-	-
Earth Cooling	Promote Ventilation	-	-	-
High rooms	Promote Ventilation	●	●	-
Pools/Evaporation	Promote Evaporation	●	-	-
Summer/Winter Rooms	Adaptation	●	-	-
Courtyard	Promote Radiant Cooling	●	●	-
Light Coloured Roof	Reflection of Solar Gains	●	●	●
Legend: ● = yes ; ○ = partially available ; - = not available				

5.2.1. Methodology

As a result of the software comparison seen in chapter 02, DesignBuilder was chosen as the best fit to undergo the following building's performance tests. The workflow has been already described before. Nevertheless, the following are the basic steps needed to evaluate the performance of a building by using this tool: insertion of project data, geometry input, model data input, simulation, evaluation, and, lastly, optimisation (although we will optimise a building in the following chapter only).

5.2.1.1. Input - Description of Digital Models

To have comparable results, the primary input settings summarised in detail in table 5.2 and 5.3 (and in the appendix, see table A.4), are identical in all the three models: climate data template,

Table 5.2 – Input settings for the simulation of the three buildings in DesignBuilder.

Climate Data	**Template (Standard):** Cairo Airport
	Latitude: 30.10 **/ Longitude:** 31.18
	ASHRAE Climate Zone: 2B
Use and Activity	**Model Options / Gainsdata ->** Lumped / **Early** / Detailed
	Model Options / Timing -> Typical Work Day / Scheduled
	HVAC and Nat Vent Operate with Occupancy: ON
	Internal Gains Operate with Occupancy: ON
	All Gains
	Power Density and Equipment: 2,16 W/m2
	Occupancy and Schedule: 0,0196 (people/m2) / 24/7
	HVAC / Nat. Vent.
	Heating Setpoint / Setback Temp. / Schedule: 18° / 16° C / 24/7
	Cooling Setpoint / Setback Temp. / Schedule: 29° / 31° C / 24/7
	Nat. Vent. / Mech. Vent. Setpints / Schedule: 24° / 10° C / 24/7
Art. Light	**Lighing:** Normalised Power Density = 2 W/m2 100 lux (LED)
HVAC and Natural Ventilation	**Mechanical Ventilation:** Free Float Simulation = OFF / Energy Simulation = ON
	Heating: Free Float Simulation = OFF / Energy Simulation = ON
	Cooling: Free Float Simulation = OFF / Energy Simulation = ON
	DHW: Free Float Simulation = OFF / Energy Simulation = ON
	Natural Ventilation: Free Float Simulation = ON / Energy Simulation = ON
	Natural Ventilation Setting (Model Options): Calculated
	Crack Template: Calculated
	Infiltration Rate: Calculated
Windows and Shading Devices	**Glazing:** Sgl Clr 6mm, Glazing Area Opens: 65% (U-Value : 5,7 W/m²K)
	Frame Construction: Painted Wooden Window Frame (U-Value : 3,3 W/m²K)
	Window Shading: OFF
	External Doors: Oak (U-Value : 2,7 W/m²K)

model options, occupancy and schedule, power density, HVAC, natural ventilation, infiltration, artificial light, openings, and shadow systems. The climate data used is the standard template Cairo Al Qahirah Airport (WMO station Identifier: 623660 - year 2002). The model data for gains was selected as early (in which internal gains are separated into various categories), and the HVAC systems were modelled using the simple calculations method. By choosing the calculated method for natural ventilation, the ventilation rate of the models was calculated using wind and buoyancy-driven pressure, opening sizes and operation, crack sizes, etc. Therefore, infiltration airflow and crack template were calculated instead of being entered. Internal gains, HVAC systems and natural ventilation were set to be operating during occupancy. All rooms and buildings share the same activity schedule (on 24/7 – 0,0196 people/m^2), and the internal gains were set at 2,16 W/m^2 (power density and equipment) and 2,0 W/m^2 100 lux (LED lighting). While the heating and cooling setpoints were used only for the energy tests, natural ventilation was set in every test to function whenever the internal temperature would be above 20°. Concerning the openings, a single glass window with a wooden frame was used in all models, and no shading devices were set. Variable settings and features, such as geometry, volumes, openings position, orientation, construction settings, are customised for each building. To mirror the reality as near as possible, extensive research has been done to find drawings, pictures, documentations, and descriptions of the analysed buildings. The plans found in the digital collections of the American University in Cairo (see Fathy, 1942; Saleh Lamei, 1987) have given an excellent basis for creating the geometry of Manzil Zainab Khatun and Hamed Said House.

Table 5.3 – Construction settings for the simulation of the three buildings in DesignBuilder.

Model	Component	Material	Term. Cond. λ (W/mK)	Density ρ (kg/m³)	Capacity c (J/kg K)	Thickness d (m)	U-value U (W/m²K)
Typology 01 Manzil Zaynab Khatun	**External Walls**	Plaster Lightweight	0,16	600	1000	0,03	1,21
		Limestone, semi hard	1,4	2000	1000	0,59	
		Lime sand render	0,8	1600	1000	0,015	
		Limestone hard	1,7	2200	1000	0,015	
	Internal Partitions	Plaster Lightweight	0,16	600	1000	0,03	0,95
		Limestone, semi hard	1,4	2000	1000	0,59	
		Plaster Lightweight	0,16	600	1000	0,03	
	Roof	Timber Flooring	0,14	650	1200	0,02	2,05
		Loose fill/powders - sand	1,74	2240	840	0,31	
		Stone limestone tiles	2,9	2750	840	0,02	
	Internal Floor	Timber Flooring	0,14	650	1200	0,02	1,67
		Loose fill/powders - sand	1,74	2240	840	0,31	
		Stone limestone	2,9	2750	840	0,02	
	Ground Floor	Stone limestone	2,9	2750	840	0,05	1,72
		Clay underfloor	1,5	1500	2085	0,5	
Typology 02 Hamed Said House	**External Walls**	Plaster lightweight	0,16	600	1000	0,02	0,77
		PhD adobe wall	0,59	1400	1000	0,56	
		Lime sand render	0,8	1600	1000	0,02	
	Internal Partitions	Plaster Lightweight	0,16	600	1000	0,03	0,63
		PhD adobe wall	0,59	1400	1000	0,56	
		Plaster Lightweight	0,16	600	1000	0,03	
	Roof	Plaster lightweight	0,16	600	1000	0,02	1,2
		PhD adobe wall	0,59	1400	1000	0,31	
		Lime sand render	0,8	1600	1000	0,02	
	Ground Floor	Stone limestone	2,9	2750	840	0,05	1,61
		Clay underfloor	1,5	1500	2085	0,5	
Typology 03 Abdullah's Building	**External Walls**	Plaster Lightweight	0,16	600	1000	0,005	2,23
		Zement Sand Mörtel	1	1600	1000	0,025	
		Brickwork	0,62	1700	800	0,125	
	Internal Part.	Brickwork	0,62	1700	800	0,125	2,16
	Roof	Concrete, High density	2	2400	1000	0,150	2,55
		Bitumen, felt/sheet	0,23	1100	1000	0,020	
		Loose fill/sand	1,74	2240	840	0,050	
		Zement Sand Mörtel	1	1600	1000	0,025	
		Concrete tiles	1,50	2100	1000	0,025	
	Internal Floors	Concrete, High density	2	2400	1000	0,15	2,9
	Ground Floor	Stone limestone	2,9	2750	840	0,02	1,43
		Zement Sand Mörtel	1	1600	1000	0,02	
		Loose fill/sand	1,74	2240	840	0,06	
		Concrete, High density	2	2400	1000	0,15	
		Clay underfloor	1,5	1500	2085	0,5	

The plans found in *Cairo – the Informal Response* (Angelil et al., 2016) have been fundamental in representing Abdullah's building.

Assumptions have been made when the information at disposal was not enough to set up the digital model precisely. Good examples are the assumptions done for different constructions elements of the buildings. With Abdullah's building and Hamed Said House, definite descriptions, and pictures, made it possible to model the structures confidently. For Manzil Zaynab Khatun, plan-sets done in different years, while coherent for most of the information given, contained slightly different information regarding wall constructions and their depth. Few information was available about the slab and roof constructions. In this case, while sticking to one set of plans (done by Lamei in 1987), assumptions based on secondary literature (Ragette, 2012, pp. 29–49) have been used to finalise these constructions in the model. Simplifications have been made if issues have been found during simulation or when comparing results. Therefore, for example, thinking about the testing time needed for simulation, the mashrabiya in the Zaynab Khatun House have been simplified as wooden cabins with simple openings with baffles (50% open), instead to model them as carved wooden surfaces. The choice to use the same set of windows in all buildings was dictated by two factors: the comparability of the models and the missing, or unprecise, information in our hands. Hamed Said house was modelled as a standalone building, while the other two have been modelled within the context. On the Eastern side of Manzil Zaynab Khatun, a volume was placed (7 by 26 meters, 11 meters high), simulating shades and adiabatic conditions that the complete building might have given. Abdullah's building has been modelled including the adjacent buildings, providing adiabatic properties to the external walls, while the opposite building shades the main façade.

5.2.1.2. Output and Simulation Sets (Free Float – HVAC)

For each typology, two kinds of simulations have been performed: free float and with HVAC systems (see table 5.4). The simulations carried in free float mode aim to calculate the operative temperatures (internal temperature) when only natural ventilation is possible. By doing so, the windows are "open" only when the operative temperature (T_O) of the room is higher than the temperature setpoint ($T_{setpoint}$ = 20° C) and higher than the outdoor temperature (T_{OUT}). To get a picture of the thermal performance of the buildings (or part of the buildings) and to compare the results obtained during the whole year, as well as in weeks that might show extreme behaviour, the tests have been done for getting thermal performance results for the entire year, as well as for summer week (19-25. August) and winter week (22-28. January). The hourly results have also given us the chance to dig further into what happens to the operating temperatures in the same building during the same day. By transforming the data result into graphics, it was possible to create a visual summary that might be helpful both for direct comparison of the buildings and to realise how the air moves through the building and with which thermal effects.

Hourly results have also been further processed, and the number of hours in which the building operative temperature is outside the comfort limits was summarised for each month. In DesignBuilder, there are many ways to predict uncomfortable hours in the building. It is possible to use methods such us Fanger's Predicted Mean Vote / Predicted Percentage of Dissatisfied relation (PMV/PPD), the Standard Effective Temperature model (SET, also known as Pierce's Two-Node model), or adaptive comfort models such as ASHRAE Standard 55, or CEN Standard 15251. Just like it was done in chapter 03, we have filtered the building simulation results to have an overview of the number of hours in which the buildings are outside of the comfort temperatures described by Givoni (1998) in its *boundaries of acceptable conditions for still air* (for hot and developing countries). This kind of operation, done at the building scale, or done by comparing different floors or rooms, might help have a short overview (and comparison) of the number of hours in one month in which T_O are higher than 29°C and lower than 18°C.

Table 5.4 – Test runs and expected data output.

TEST NUMBER	TYPOLOGY	INPUT			OUTPUT							
		FREE FLOAT	HVAC	Simulation Period	Monthly Temperatures	Hourly Temperatures	Hourly Temp. Distribution	Yearly Heat Gains	Hourly Heat Gains	Nat Vent / Infiltration	Yearly Energy Demand	Monthly Energy Demand
Typ01_FF_Y	Manzil Zaynab Khatun	●	-	Y	●	●	-	●	●	●	-	-
Typ01_FF_S	Manzil Zaynab Khatun	●	-	SW	-	●	●	-	●	●	-	-
Typ01_FF_W	Manzil Zaynab Khatun	●	-	WW	-	●	●	-	●	●	-	-
Typ01_HVAC_Y	Manzil Zaynab Khatun	-	●	Y	-	-	-	-	-	-	●	●
Typ02_FF_Y	Hamed Said House	●	-	Y	●	●	-	●	●	●	-	-
Typ02_FF_S	Hamed Said House	●	-	SW	-	●	●	-	●	●	-	-
Typ02_FF_W	Hamed Said House	●	-	WW	-	●	●	-	●	●	-	-
Typ02_HVAC_Y	Hamed Said House	-	●	Y	-	-	-	-	-	-	●	●
Typ03_FF_Y	Abdullah's Building	●	-	Y	●	●	-	●	●	●	-	-
Typ03_FF_S	Abdullah's Building	●	-	SW	-	●	●	-	●	●	-	-
Typ03_FF_W	Abdullah's Building	●	-	WW	-	●	●	-	●	●	-	-
Typ03_HVAC_Y	Abdullah's Building	-	●	Y	-	-	-	-	-	-	●	●
Typ01_SA	Manzil Zaynab Khatun	●	-	AUG	Sensitivity Analysis							
Typ02_SA	Hamed Said House	●	-	AUG	Sensitivity Analysis							
Typ03_SA	Abdullah's Building	●	-	AUG	Sensitivity Analysis							
Legend: Simulation Period: Y=Year; SW=Summer Week; WW=Winter Week; AUG=August (full month)												

Why have we decided to follow this method? The PMV/PPD and SET models have already been criticised because of low prediction accuracy. Researches have shown that by using the first method, the thermal sensation was correctly predicted only one time out of three, while by using the second one, skin temperatures were overestimated and skin wittedness underestimated (Cheung, Schiavon, Parkinson, Li, & Brager, 2019; Doherty & Arens, 2008; Földváry Ličina et al., 2018). Adaptive comfort models, the most spread models used within BPSS, are based on the idea that building occupants' thermal expectations lie in a temperature range based on outdoor temperatures and their past thermal history (de Dear & Brager, 1998). Givoni criticised these methods because they do not address un-air-conditioned buildings, they do not take into account adaptive users (that react to temperature change by clothing modification, opening or closing windows, activity modifications, etc.), and that the comfortable temperature ranges are too narrow (e.g. results may suggest the use of air-conditioning when natural ventilation might be enough). (While this last critic might be still valid today, adaptive models nowadays have been further developed by including also ranges for operative temperatures for buildings without mechanical cooling system - see e.g. EN15251:2006 E p.27). Therefore, by starting with a chart visualising the *boundaries of acceptable conditions for still air* (see figure 5.8, above), in which he was able to set acceptable conditions for hot-developing countries at temperatures between 18 and 29°C (dry-bulb), he developed the *Building Bio-Climatic Chart* (BBCC, see figure 5.8, below). In the BBCC, comfort boundaries can increase in hot climates if cooling options such as daytime ventilation, high mass, nocturnal ventilation, direct evaporative cooling, and indirect evaporative cooling by roof ponds are implemented (1998, pp. 36–45).

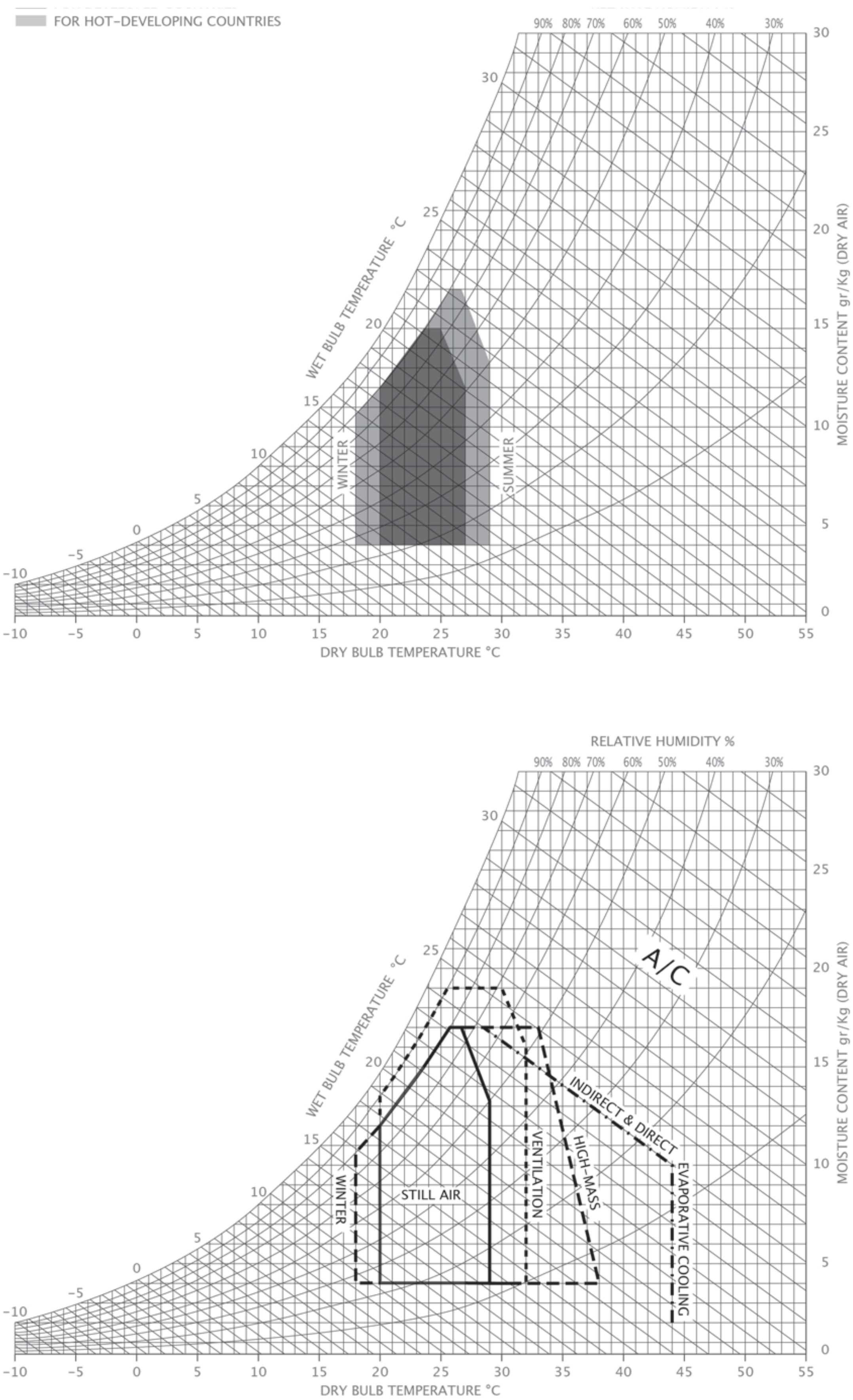


Figure 5.8 – Givoni's Boundaries of Acceptable Conditions for Still Air (above) and Givoni's Building Bio-Climatic Chart (GBCC), showing the different design strategies and boundaries of the passive cooling approaches for hot, developing countries (below). (Givoni, 1998, p. 38,45).

The HVAC system simulations aim to calculate the energy needed to heat and cool down the buildings. While natural ventilation is still possible ($T_{setpoint}$ = 20°C), active cooling starts when T_O reaches 29°C (setback at 31°C), and active heating when T_O is under 18°C (setback at 16°C). Both cooling and heating systems have been set with a coefficient of performance (CoP) equal to one. Therefore, the kWh needed for these mechanical features is easy to read and eventually might be used for further system optimisation calculations. The heating and cooling demand (monthly results) are shown as building averages and single zones (Manzil Zaynab Khatun and Abdullah's building).

The last part of the tests wants to identify, for each model, what are the design variables that have the greatest and least impact on comfortable operative temperatures. Therefore, by taking the free float models as a basis, a sensitivity analysis is carried out using DesignBuilder. For doing that, it is necessary to clarify the aim of the analysis and the variables (and their relative options) used for the test. Regarding the purpose, what we want to assess these models for, is the number of discomfort hours during August. Depending on the typology results obtained with a standard simulation, the model for determining comfort hours is chosen (ASHRAE 55 Adaptive 90% for good performing models, and Adaptive Comfort CEN 15251 Cat III for models that might perform poorly). When the simulation has run two-hundreds iterations (or more, if the model needs it), the results are shown in the form of a complete report. Here, besides the adjusted R squared value results, the regression coefficients for each variable are given (regression coefficient, standard regression coefficient, standard error and p-value). To increase confidence in the results, depending on the adjusted R-squared value results and the p-value of the variables, further tests with fewer variables, or different ones, are done. In table A.5 in the appendix are visible the options in detail.

5.2.2. Results and Observations

5.2.2.1. Outdoor and Operative Temperatures (Yearly Results to Single Day)

The first obtained results, also shown in figure 5.9, give a general overview of minimum, maximum, and average temperatures of the outside temperature (T_{OUT}) and the three buildings (operative temperature: T_O). The T_O results given are building averages. That means that the results do not show internal temperature differences within different dwellings' spaces or floors. Nonetheless, what they offer can be used as a baseline for having a first comparison of the buildings (and a comparison against the T_{OUT}) and observing how broadly T_O fluctuates. That might be beneficial to understand how the building performs as a system and to get a first understanding of comfort hours.

What can be observed by looking at T_{OUT} is that temperatures range from 4,9°C in January to 43,9°C in July, and average temperatures fluctuate between 13,7°C and 29,2°C (in January and July). Focusing only on one month, the monthly fluctuation temperature range goes from 15,9°C (August) to 29,0°C (April). The daily T_{OUT} fluctuation is better represented when looking at the hourly results of the winter and summer weeks. During the winter week, we can notice that on January 22nd, T_{OUT} shifts from about 4°C to a bit more than 16°C, while on another winter day, January 25th, T_{OUT} constantly remains around 11°C (+/- 2°K). During the summer week, we notice that on August 21st, temperatures reach 25°C in the morning hours and about 37°C during the afternoon. On August 25th, while the lowest temperature reaches 25°C, the day highest is about 32°C.

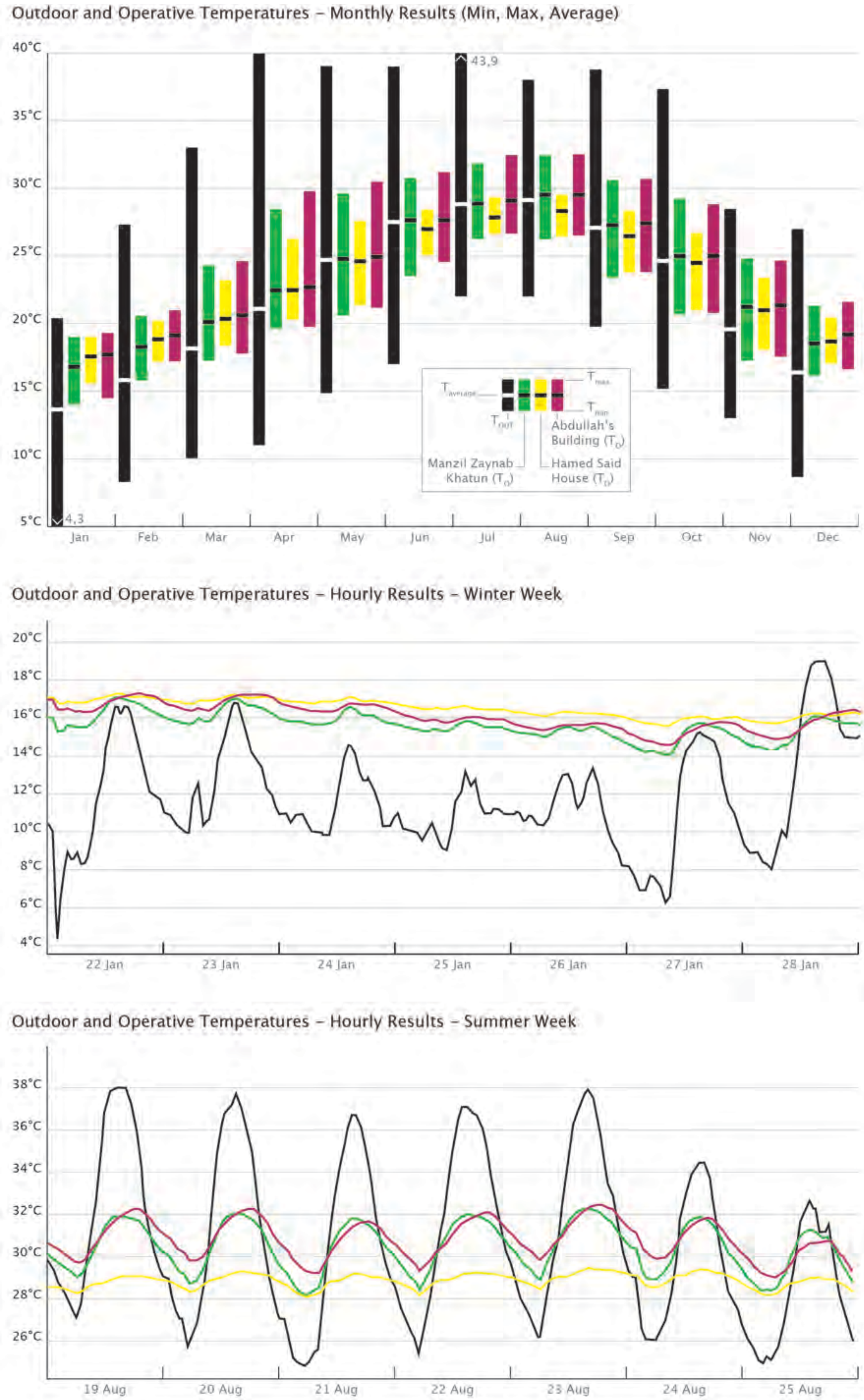


Figure 5.9 – Outdoor and operative temperatures of the three buildings – Monthly and hourly results.

Table 5.5 – Characteristics of rooms chosen for hourly results displayed in Figure 5.10 and 5.11.

	Room Area	Room Height	Room Vol.	External Openings (m^2)				External Walls (m^2)				Window to Wall Ratio (%)				Openings to Internal Room
Room	m^2	m	m^3	North	East	South	West	North	East	South	West	North	East	South	West	
01	15,8	2,4	37,9	-	-	1,5	2,4	-	-	16,3	16,2	-	-	9,4	14,8	N/E
02	11,8	3,9	46,0	-	1,0	1,0	-	-	14,3	16,3	14,3	-	7,0	6,1	-	N
03	12,4	2,6	32,2	-	-	-	1,1	-	-	-	8,3	-	-	-	13,3	E/S
Legend: 01=Manzil Zaynab Khatun-SW Room, 3rd fl.; 02=Hamed Said-ESW Bedroom; 03=Abdullah's Building-W bedroom, 4th fl.																

Even though with different average temperatures, the monthly temperature fluctuation of the three buildings shows a similar pattern as with T_{OUT}; during summer and winter months, T_O fluctuates less than in spring and autumn. Nevertheless, while Hamed Said house T_O fluctuation goes from a minimum of 2,6°K (in July) to a maximum of 6,3°K (in May), the ΔT is more significant in the other two buildings. The difference between minimum T_O and maximum T_O varies from 4,6°K to 9,0 in Manzil Zaynab Khatun and from 3,8 to 10°K in Abdullah's building. When also looking at the average T_O of the three buildings, we can recognise Abdullah's building as the one with slightly higher temperatures throughout the year.

The hourly results of the winter week show that all three buildings have an average T_O higher than T_{OUT} most of the time. Yet, what comes out when looking at the daily T_O fluctuation is that Hamed Said house, while being most thermally comfortable than the other buildings, has very little T_O daily fluctuation. It seems that the building reacts slowly to the changing T_{OUT}. A very different story can be read by looking at Manzil Zaynab results; while being the building that has more T_O fluctuation during this week, it is also the building that reacts faster at changing T_{OUT}. Although it has a curve resembling the oldest building, Abdullah's building seems to be slower in realising the heat than Zaynab Khatun house.

By observing the summer week results, these phenomena can be seen in an amplified way, thanks to the higher heat gains and to fluctuation in T_{OUT} that can reach about 12°K a day. Here again, we can see two similar patterns, namely the ones of manzil Zaynab Khatun and Abdullah's building. The first one being highly reactive to T_{OUT} changes has a weekly average T_O of 30,5°C with a fluctuating temperature of about +/- 2,1). With a weekly average T_O of 30,9°C with a fluctuating temperature of about +/- 1,7) while reaching slightly higher temperatures than the oldest building, Abdullah's building seems unable to realise the heat during the night Zaynab Khatun house. During this week, Hamed Said house performed better than the other two buildings. Yet, while it can keep T_O constant at about 29°C with a variation of about +/- 0,7°K, it seems it cannot release the heat as fast as the other two buildings do.

In figures 5.10 and 5.11, different hourly results regarding temperature variations, heat gains, natural ventilation and infiltration of one room in each building are displayed. Both figures show the hourly results during two days (22-23. January and 19-20. August). Besides having a similar size and a similar function (bedroom), each room has at least one external wall towards the West, and all rooms are placed on the highest floor of the building. The bedroom of Manzil Zaynab Khatun, placed on the third floor, is the lowest of the set (2,4 m, see also table 5.5). It has two external walls with a total window-to-wall ratio (WWR) of 12,1%, which varies between 9,4%

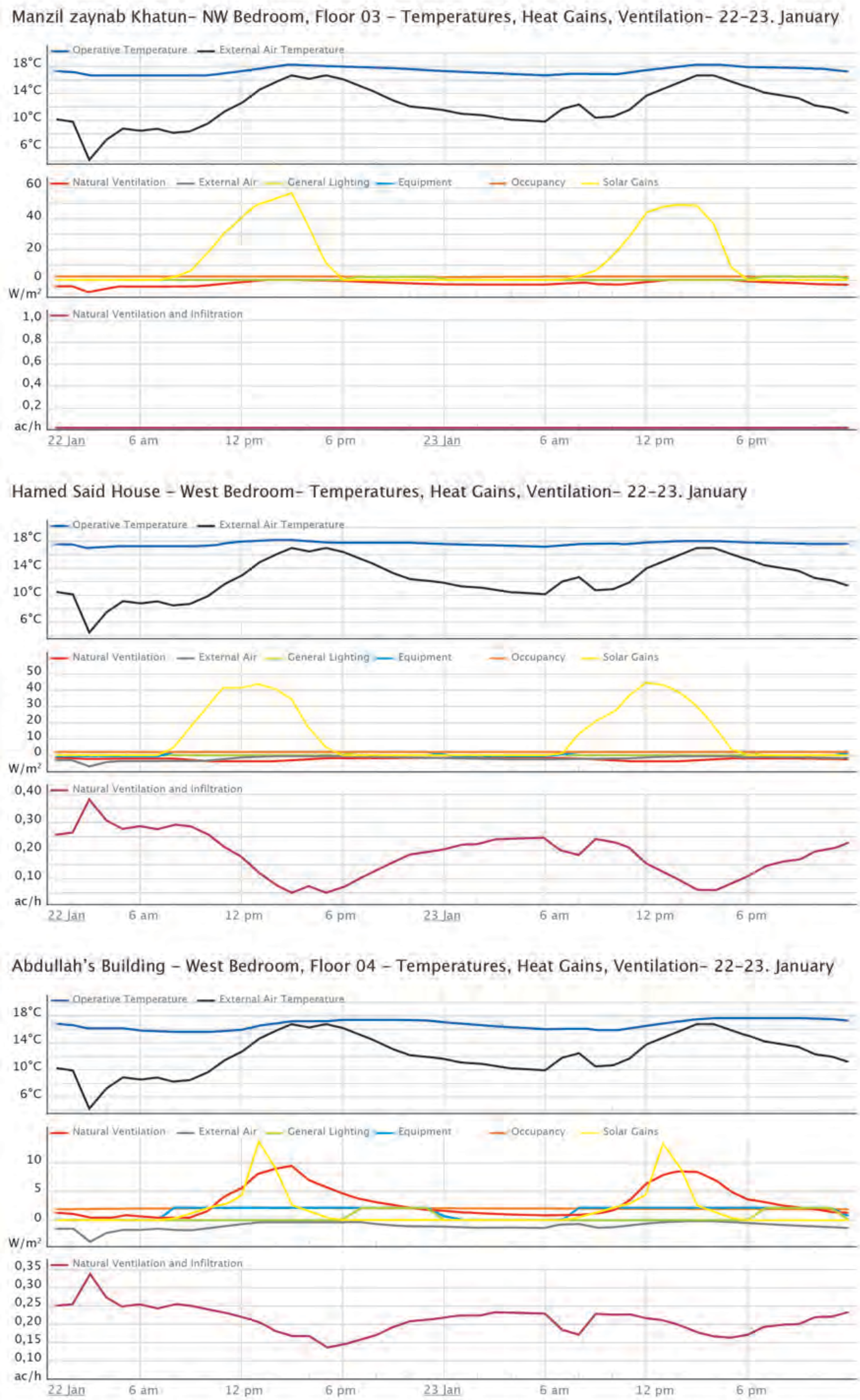


Figure 5.10 – Temperatures, heat gains and ventilation of the three buildings – Hourly results (Winter).

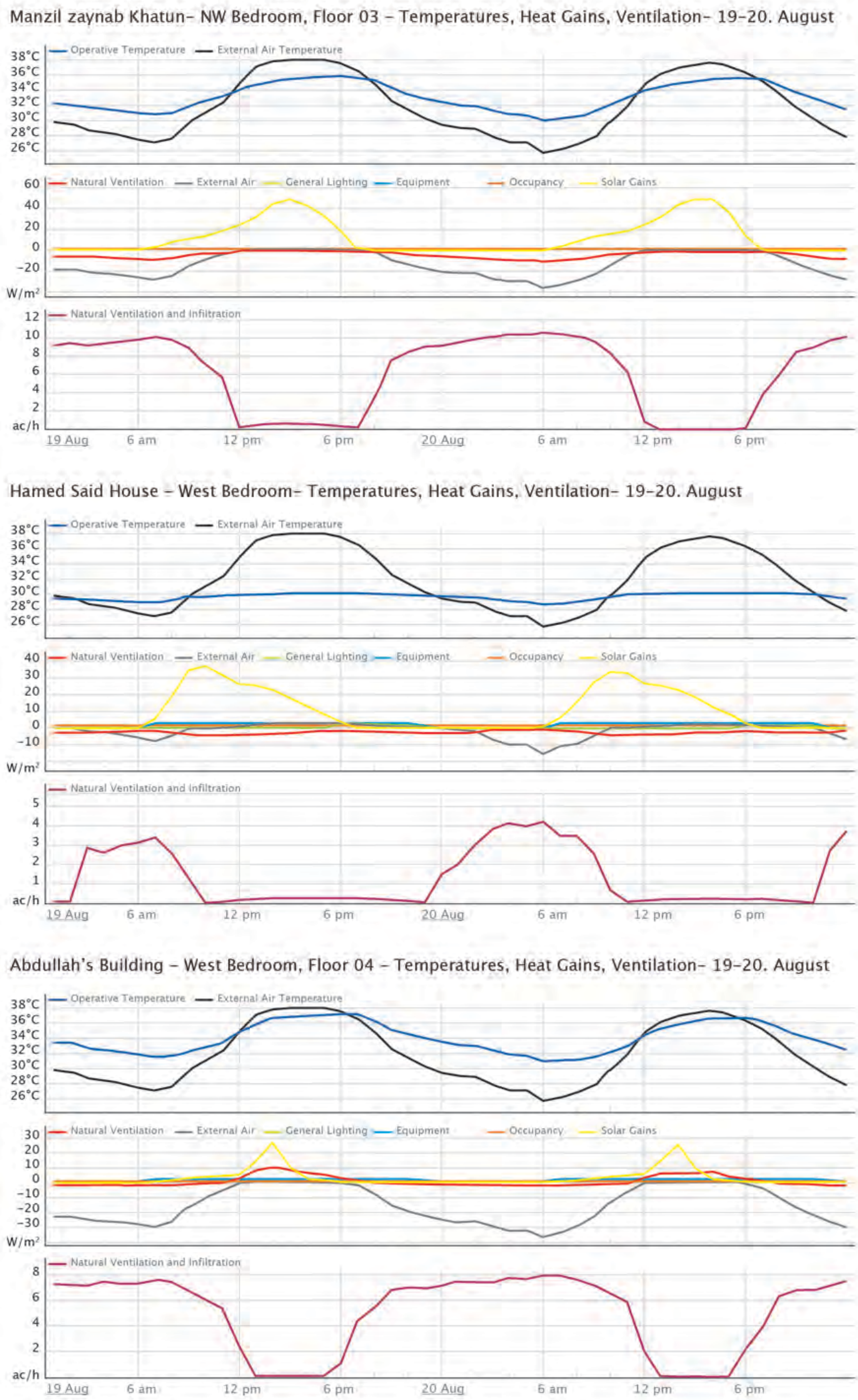


Figure 5.11 – Temperatures, heat gains and ventilation of the three buildings – Hourly results (Summer).

(South wall) and 14,8% (West wall) and has internal access (also for internal natural ventilation) toward North and East. The bedroom of Hamed Said is the smallest (11,8 m^2) and the highest (3,9 m). It has three external walls (East, South and West) and internal access towards North. With one of the three walls without openings, the total WWR is 4,5%, and it varies between 6,1% (South wall) and 7% (East wall). The West bedroom that we find in Abdullah's building is similar to Hamed Said's, but its height is 2,6 m, making it the smallest room in cubature (32,2 m^3). The room has only one West window measuring 1,1 m^2, and the WWR is 13,3%.

So how do these different rooms behave during the different periods? Let us start with the observations about heat gains and ventilation during the January days. In room 01 (Manzil Zainab Khatun, South-West room on the third floor), most heat gains are solar. The position and size of the windows permit the room to gain solar gains between 7 AM and 6 PM, peaking at about 58 W/m^2 at 3 PM. Some minor heat losses due to internal natural ventilation (towards other rooms) can be seen during these days, and virtually no natural ventilation and infiltration are recorded. In room 02 (Hamed Said, Bedroom on the ground floor), the solar gains are responsible for most heat gains. While the curve looks like the one of room 01, we can observe that thanks to the Easter window, the solar gains increase fast during the morning hours (about 41 W/m^2 at11.00 AM), peak at around 43 W/m^2 at 1.00 PM, and then they slowly decrease. The assumed infiltration ranges between 0,05 and 0,38 ac/h, and it is inversely correlated to the T_{OUT}. In Room 03 (Abdullah's building, West bedroom on the fourth floor), we notice that solar gains are relatively contained compared to the other two rooms, peaking at about 14 W/m^2 just after midday. This might be due to the opposite building that blocks solar gains most of the day and the position of the only window towards the West. On the other hand, another internal gain that considerably affects the heat gain calculations is internal ventilation. The heated air from the adjacent spaces heats the room for most of the day and peaks at around 9 W/m^2 at 3.00 PM. The assumed infiltration ranges between 0,14-0,34 ac/h.

In August, in room 01, while most heat gains still come from the sun (starting at 6 AM and ending at 6.30 PM, with the peak at about 52 W/m^2 at 3.00 PM), some heat losses can also be observed. Losses due to internal natural ventilation peak when T_{OUT} is at minimum, and peak to about -11W/m^2. External air coming through natural ventilation and infiltration at the rate of 10-11 ac/h permits heat losses up to about -29 W/m^2. Here, as also in the other rooms results, we can see clearly how the ventilation strategy works in practice: in winter, being T_{OUT} below 20°C (the setpoint for natural ventilation), the windows remain constantly closed. In summer, being T_{OUT} and T_O always higher than 20°, we see high infiltration rates due to natural ventilation, whenever T_O is higher than T_{OUT}. By looking at room 02, we can observe that, especially during the late hours of the morning, solar gains exceed 30 W/m^2, and heat losses might reach 15 W/m^2 because of external air (3-4 air changes per hour). In the third room, we can observe solar gains intakes which are significant only between midday and 4 PM (they peak at about 28 W/m^2. And here we can see that, even though the room is ventilated during the whole night and most parts of the day (about 7-8 ac/h), the temperature remains higher than comfortable. Generally speaking, during this time range, room 01 can keep T_O below T_{OUT} for about 9 hours, room 02 can maintain a lower T_O than T_{OUT} for most of the day (about 15 hours), while Room 03 can do so only for 6 hours.

When delving into the results of the temperature obtained at room level, it is possible to understand better under which circumstances – and within which building system – T_O might be uncomfortable. Therefore, the hourly results are visually represented in figures 5.12-5.15. In these graphics, it is possible to see a thermal picture of the buildings at two specific times of a particular day. For Manzil Zaynab Khatun and Abdullah's building, three representative floors were chosen to observe temperature differences on the ground floor, a central floor, and the highest floor. (Having only one storey, Hamed Said house was represented as it is.)

The first set of simulations represent the performance of the three buildings on January the 22nd at 9 AM (graphics on the left-hand side) and 10 PM (graphics on the right-hand side). At these times, T_{OUT} is 8°C and 12,2°C, respectively. At 9 AM, the T_O of Manzil Zaynab Khatun range between 15°C (ground floor) and 18°C (room on the first floor). At 10 PM, the lowest temperature is found again on the ground floor – 17°C, while the rooms on the third floor have reached temperatures between 17 and 19°C. During the same winter day, Hamed Said house shows a room T_O range between 17 and 19°C virtually for the day. The coldest part of the house includes the loggia and the old artist's studio. In Abdullah's building what can be observed in the morning results, is that making an exception for the distribution shaft (that does not have a roof), the T_O range from 14°C on the Western side of the second floor to 17°C of Eastern side of both the ground and the last. During the evening time, a temperature between 16 and 19°C is reached in the building. Again, the Eastern side, which is embedded between the other three buildings, remains warmer than the one with the "free" façade.

The second set of simulations represent the performance of the three buildings on August the 19th at 8 AM (graphics on the left-hand side) and 5 PM (graphics on the right-hand side). At these times, T_{OUT} is 27,8°C and 38,0°C, respectively. In the early hours of the day, Manzil Zaynab Khatun operative temperatures range from 28 to 34°C. The whole ground floor, the Northern distribution shaft on the first floor, the Eastern corridor, and the loggia are the coldest spaces and are still in a comfortable temperature range. In the afternoon, temperatures range from 31°C (ground floor and Northern distribution shaft) to 36°C (on the third floor). Hamed Said house spaces reach temperatures within the range of 28-30°C during the whole day. Without considering the open distribution shaft, Abdullah's room temperatures range from 28 to 35°C in the morning and 30 to 37°C in the afternoon. By taking the ground floor as a reference, a ΔT of +4°K was found on the second floor and a ΔT of +7°K on the fourth floor at 8 AM. In the afternoon, a ΔT of +3°C was measured on the second floor and +7°C on the fourth.

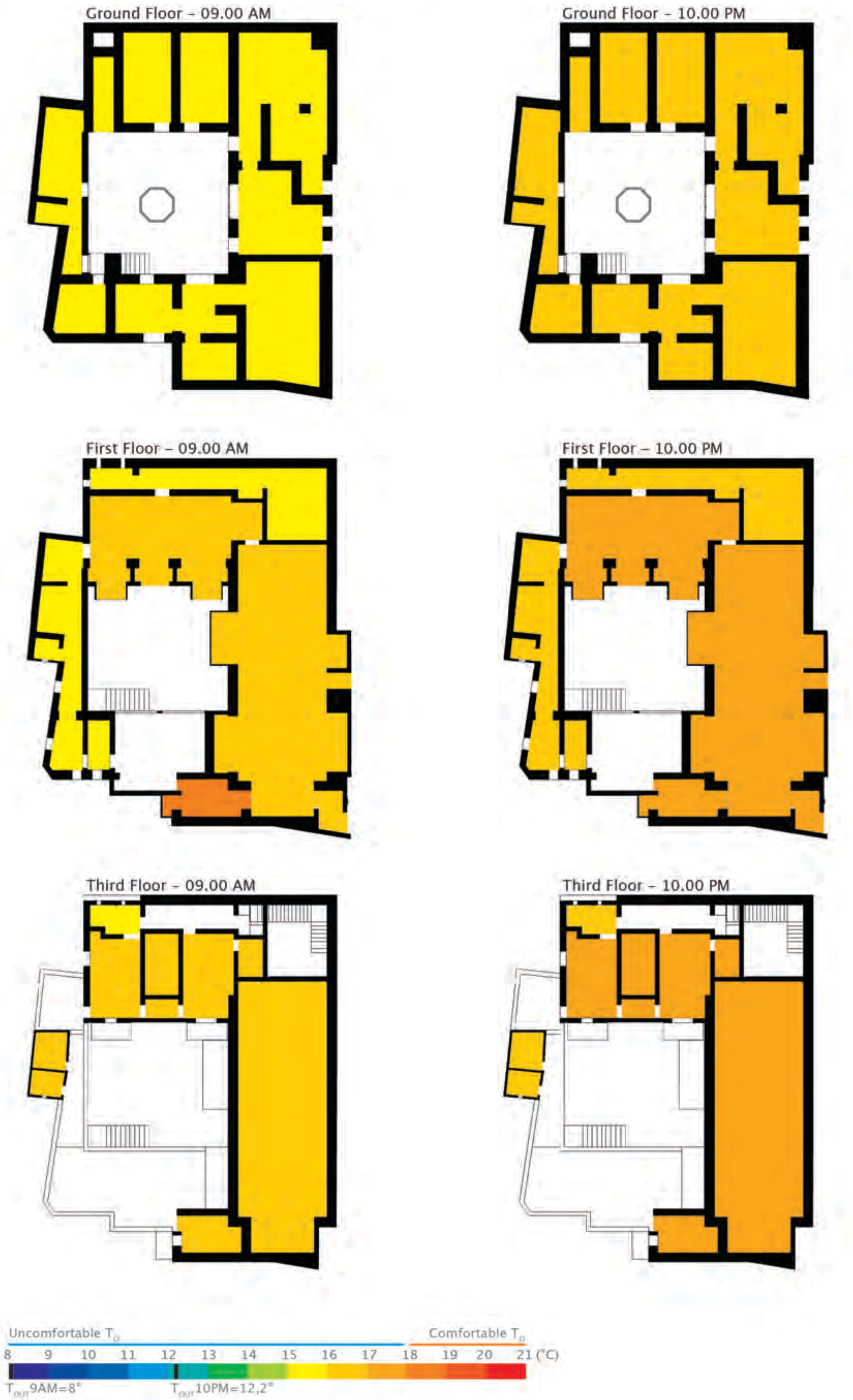


Figure 5.12 – Operative temperatures of Manzil Zaynab Khatun – 22. January at 09:00 AM (left), 22. January at 10:00 PM (right).

Figure 5.13 – Operative temperatures of Hamed Said House and Abdullah's Building– 22. January at 09:00 AM (left), 22. January at 10:00 PM (right).

Figure 5.14 – Operative temperatures of Manzil Zaynab Khatun – 19. August at 08:00 AM (left), 19. August at 05:00 PM (right).

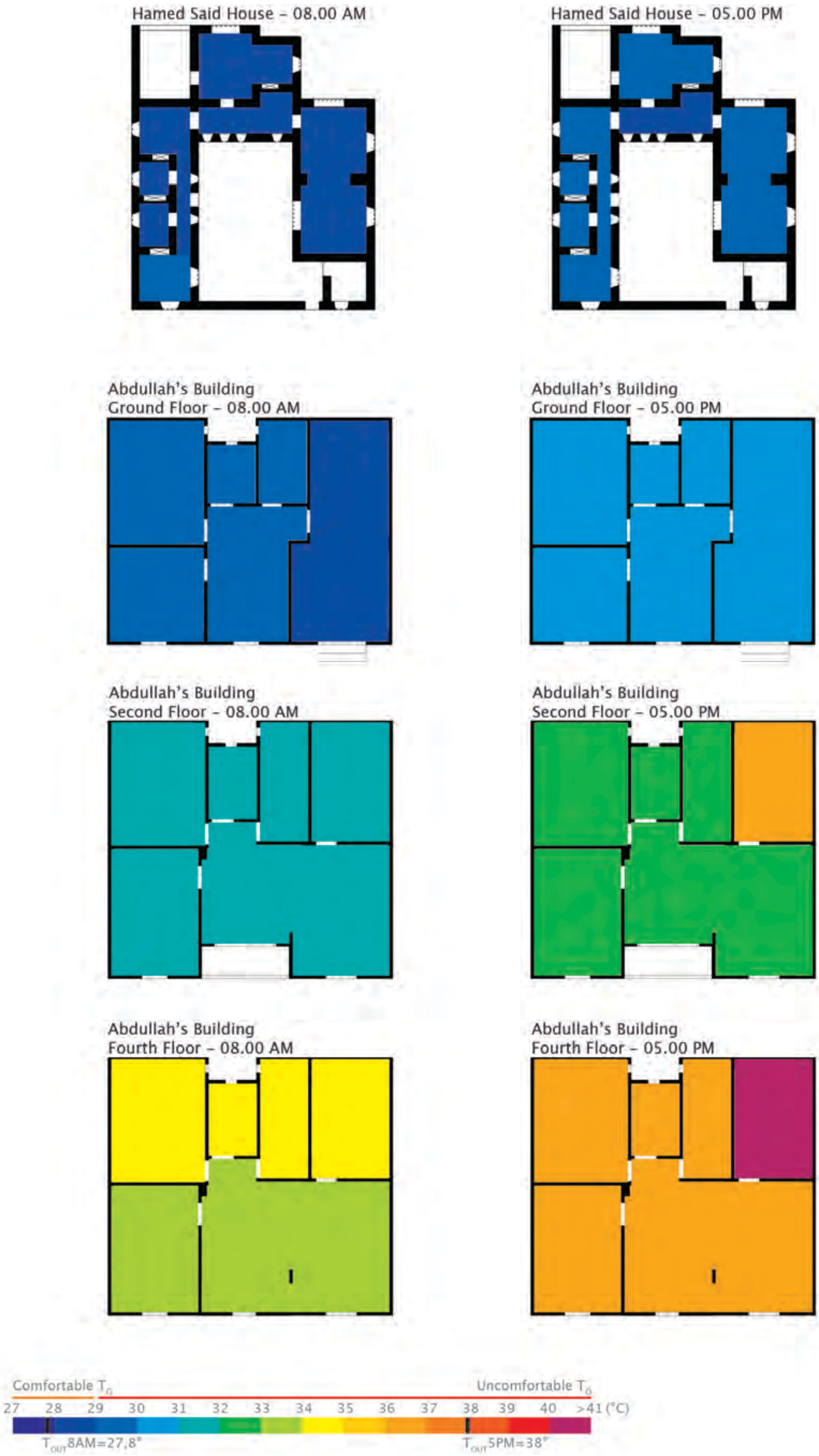


Figure 5.15 – Operative temperatures of Hamed Said House and Abdullah's Building - 19. August at 08:00 AM (left), 19. August at 05:00 PM (right).

5.2.2.2. Outdoor and Operative Temperatures (Temperatures Above 29°C and Below 18°C)

The last part of the study of buildings in free float mode is carried out to observe how many hours the buildings (or building parts) exceed comfort temperature during a month. Yearly results indicate the number of hours related to the total of 8.760 hours. Monthly results are dependent on the number of days that each month has, as it follows:

- February has 672 hours,
- April, June, September, November have 720 hours,
- January, March, May, August, October, December have 744 hours.

Again, before going into the buildings' results (see figure 5.16), describing the results obtained within outdoor temperatures (T_{OUT}) makes sense. Yearly results indicate that from a total of 8.760 hours (=100%), T_{OUT} is above 29°C for 1.625 hours (18,6%) and below 18°C for 2.643 hours (30,2%). Temperatures above 29° can be seen between March and November, and during the warmest months of June to August, temperatures stay above 29°C for about half of the time. Temperatures above 33°C can be expected for 104 to 132 hours a month. Colder temperatures than 18°C can be seen between October and June, and during winter, they tend to stay below 18°C for most of the month: 529 hours in December, 664 hours in January, 476 hours in February. Temperatures below 14°C are reached 190 hours in December, 414 hours in January, 229 hours in February.

When looking at the yearly results of Manzil Zaynab Khatun (whole building), the following is observed. Yearly results indicate T_O above 29°C for 1.135 hours (13,0%) and below 18°C for 1.170 hours (13,4%). Temperatures above 29° can be seen between May and October, and from July to August, temperatures stay above 29°C for about a half, or more, of the time. During August, about 75% of monthly hours exceed a T_O of 29°C (449 hrs). Temperatures above 31°C can be expected in July (11 hours) and August (105 hrs). Colder T_O (<18°C) can be found from November to March, with the highest share in December (238 hrs), January (635 hrs) and February (236 hrs). Temperatures below 16°C reach significant values during January (158 hrs).

Yearly results given by the simulations of Hamed Said house show T_O above 29°C for 105 hours (1,2 %) and below 18°C for 852 hours (9,7 %). The months between March and June and September to November do not show T_O outside the range 18-29°C. Temperatures above 29° can be seen between July and August, with a peak of 88 hours in August. Temperatures above 30°C are not to be expected. In winter, Hamed Said house can reach colder temperatures than 18°C in December (173 hrs), January (555 hrs) and February (124 hrs). The only month when the temperature can reach 16° or less, is January (179 hours below 17°C, and 24 hours below 16°C).

In Abdullah's building, the yearly results show that about 18,8 % of hours (1.117 hrs) are above 29°C, and 7,1% are below 18°C (625 hrs). The months of March, April, October do not show T_O outside the range 18-29°C in a significant manner (< 6 hrs). Temperatures above 29°C can be found in May (18 hrs), June (125 hrs), July (365 hrs), August (484 hrs) and September (119 hrs). The months of July and August are the only ones with temperatures exceeding 31°C (48 hours in July and 122 in August) and reaching 32°C (July: 15 hrs; August, 26 hrs). During the colder months, T_O below 18°C are to be found in November (15 hrs), December (112 hrs), January (448 hrs), and February (47 hrs). In January, temperatures reaching below 15°C were recorded for 15 hours.

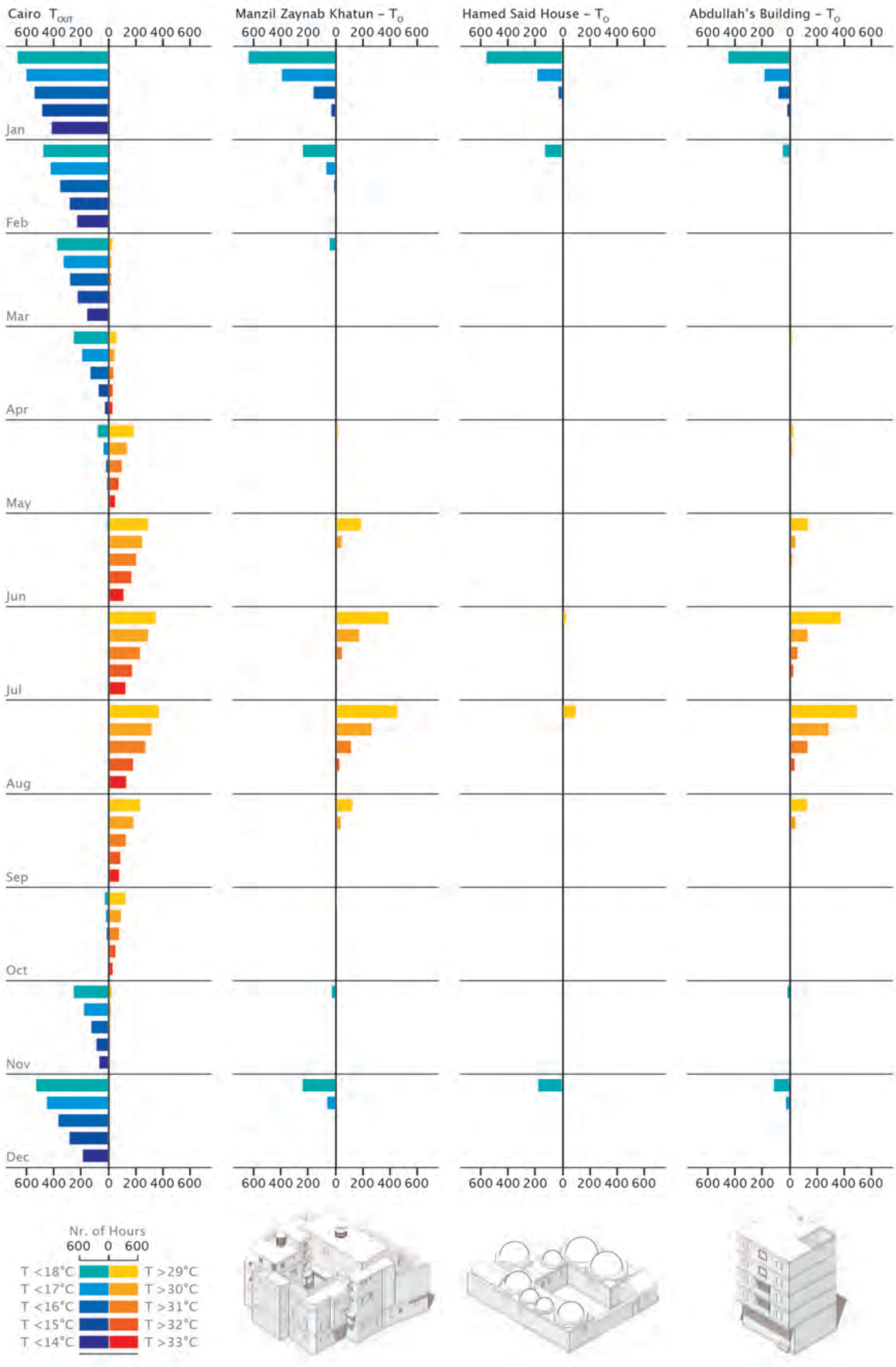


Figure 5.16 – Outdoor and operative temperatures above 29°C and below 18°C of the three buildings – Hourly results.

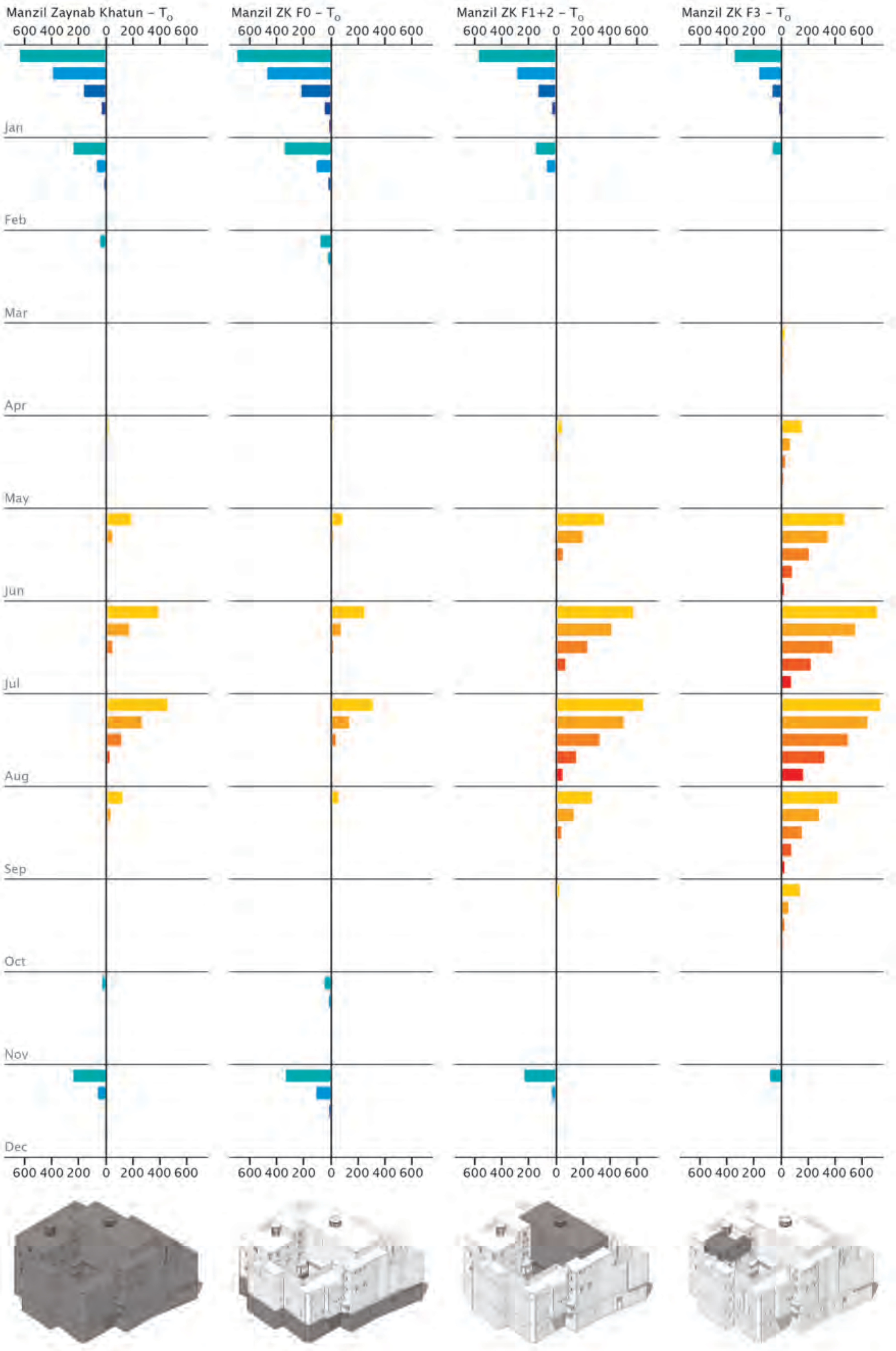


Figure 5.17 – Operative temperatures above 29°C and below 18°C of Manzil Zainab Khatun – Hourly results (F0 = Ground Floor / F1+2 = Central Hall East / F3 = Upper Room – Third Floor North).

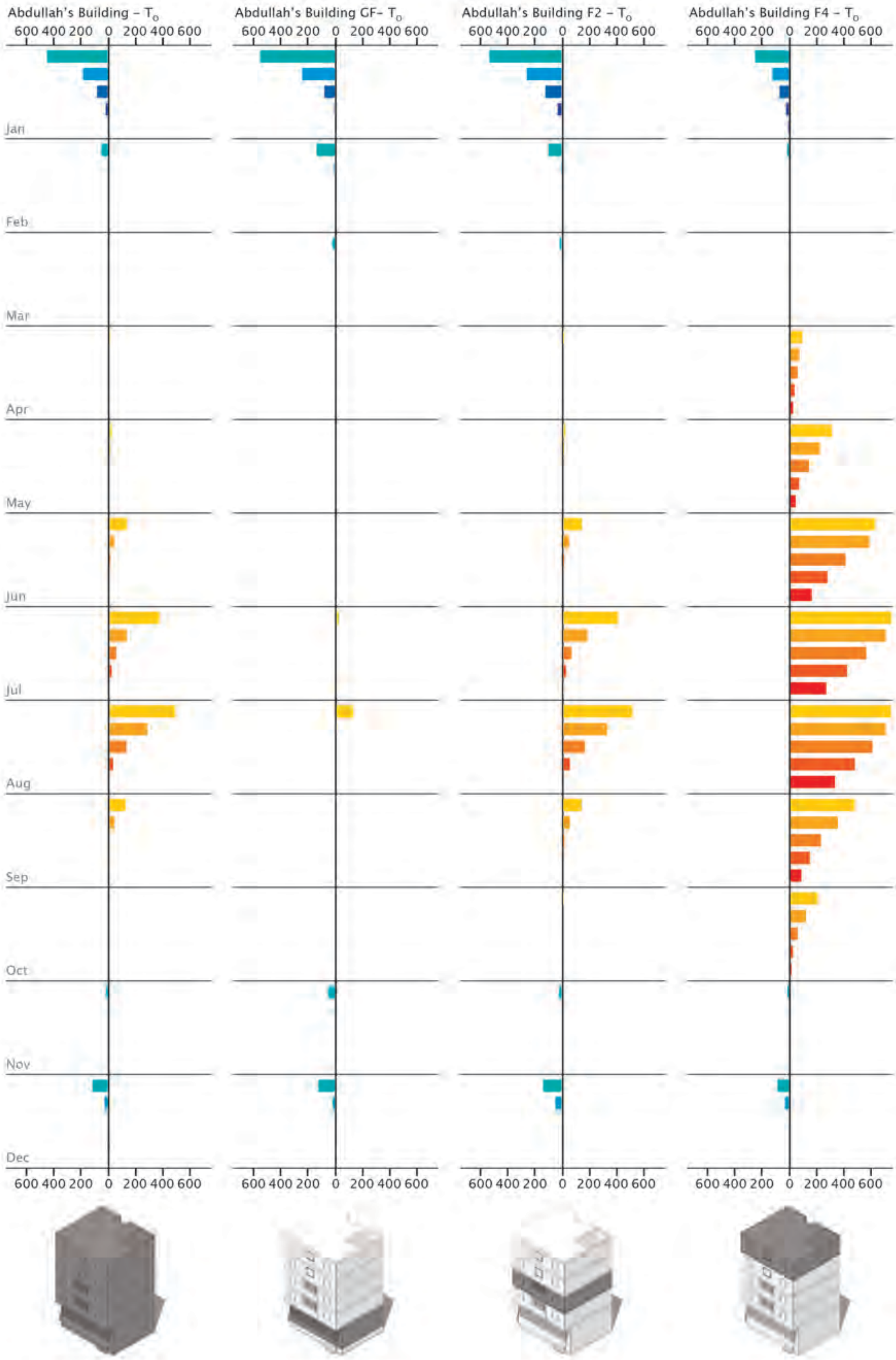


Figure 5.18 – Operative temperatures above 29°C and below 18°C of Abdullah's Building – Hourly results (F0 = Ground Floor / F2 = Second Floor / F4 = Fourth Floor).

In figures 5.17 and 5.18, the results of buildings with more than one floor have been extrapolated to see the internal differences and how more detailed results might give a different picture than the one given by building averages. In figure 5.17, we see again the results obtained from the building average, then we have the results of the whole ground floor (called F0), the central hall on the first floor (called F1+2), and an upper room on the third floor (called F3). The yearly number of hours with temperatures exceeding 29° are respectively 666 (F0=7,6%), 1.867 (F1+2=21,3%) and 2.598 (F3=29,7%), while the number of hours in which temperatures are below 18°C are 1.473 (F0=16,8%), 938 (F1+2=10,7%) and 478 (F3=5,5%).

The warmest months in all three cases are between July and August, with the upper floors having exceeding temperatures already starting in June. On the ground floor (F0), temperatures reach their highest number of hours in July (238 hrs) and August (302 hrs), and the threshold over 31°C resulted in being reached for 25 hours in August. In the central hall (F1+2), temperatures are higher than 29°C for 565 hours (out of 744) in July and 641 (out of 744) in August. Throughout all summer months, there is a considerable number of hours in which T_O is over 31°C: in June, 42 hours are counted, in July 225 (hrs), in August 315 (hrs), and in September the 30th. The room on the last floor of the building (F3) counts more than 100 hours per month with T_O higher than 29° in all months between May and October with a peak in July and August (704 and 728 hours). Temperatures above 33°C were recorded in June (10 hrs), July (64 hrs), August (153 hrs) and September (15 hrs).

The colder months are recorded between November and March. Within these months, on the ground floor (F0), T_O is below 18°C for 74 hours in March, about 300 hours in December and February, and almost all hours (690 out of 744) in January. During this month, a considerable number of hours, 41, T_O is below 15°. The central hall (F1+2) results show a similar pattern with a T_O below 18°C for 567 hours in January, 143 in February, and 228 in December. The highest number of hours in which T_O is below 15° is January (22 hours). In the room on the last floor (F3), in December T_O is below 18°C for about 78 hours, in January for 341 hours, and in February for 59 hours. The number of hours in which T_O is below 16°C is 60 (in January), and the one below 15°C is not significant (8 hours in January).

For Abdullah's building, as figure 5.18 shows, besides the average building temperatures, also the temperatures in different floors were studied. The yearly number of hours in which T_O exceed 29°C is 138 (1,6%) on the ground floor (F0), 1.208 (13,8%) on the second floor (F2), and 3.169 (36,2%) on the fourth floor (F4). The number of hours in which temperatures are below 18°C is 842 (F0=9,6 %), 801 (F2=9,1%), and 358 (F4=4,1%).

Regarding the warmest months, each floor has a different range of months in which T_O is higher than 29°C. The ground floor (F0) reaches temperatures above 29°C only in July (17 hours out of 744) and August (121 hrs). On the second floor (F2), about 135 hours are above 29°C in June and September, while in July and August, between 403 and 510 hours are uncomfortable. In July T_O above 32° were recorded for 20 hours, while in August for 49 hours. Temperatures above 29°C can be found on the fourth floor (F4) between April and October. The warmest months show a number of hours above 29°C as follows: 304 hours in May, 623 hours in June, 744 in July, 741 in August, and 472 in September. Temperature above 33°C can be found as follows: 18 in April, 37 in May, 156 in June, 263 in July, 326 in August, and 78 in September.

When observing the results gained during the colder months, we can see that in the F0, temperatures below 18°C are reached between November and March. The highest amount is recorded in January (550 hrs), February (135 hrs), and December (123 hrs). T_O below 16°C are reached only in January (78 hrs). On the second floor (F2), T_O below 18°C are reached in January (534 hrs), February (95 hrs), March (16 hrs), November (21 hrs), and December (60 hrs). Temperatures touch 15°C only in January (29 hrs). On the fourth floor (F4), T_O is below 18°C in the months of November (11 hrs), December (86 hrs.), January (248 hrs.), and February (13 hrs). In December, T_O is below 15°C for 20 hours.

5.2.2.3. Heating and Cooling Demand

The results from the simulations using the HVAC system are represented graphically in figures 5.19-5.21. As in the results just discussed, the heating and cooling demand have been compiled as whole building results (see figure 5.19) and as different spaces or floors within one building (Manzil Zaynab Khatun in figure 5.20 and Abdullah's building in figure 5.21). For comparison purposes, results are given in kWh/m^2.

Starting with a general overview of the heating energy demand, the simulations show that Manzil Zaynab Khatun needs yearly 6,9 kWh/m^2, Hamed Said house 2,5 kWh/m^2, and Abdullah's building 2,5 kWh/m^2. Regarding the cooling energy demand Manzil Zaynab Khatun needs yearly 27,7 kWh/m^2, Hamed Said house 1,5 kWh/m^2, and Abdullah's building 37,0 kWh/m^2.

In the Manzil Zaynab Khatun, the heating system should work between November and March to maintain TO in the comfort range, with the highest consumption months being January (4,5 kWh/m^2), February, and December (both 1,0 kWh/m^2). Between May and October, the cooling system will help in keeping lower temperatures than T_{OUT}. In summer, the months in which the cooling system is needed the most are June, July and August, with a cooling demand of 4,3 kWh/m^2, 8,5 kWh/m^2, and a peak of 10,5 kWh/m^2. In the Hamed Said house, temperatures stay virtually in the comfort zone from March to June and from September to November. Therefore, no heating or cooling energy is needed during these months. Heating consumption reaches between 0,1-0,3 kWh/m^2 in December and February and peaks at 2,0 kWh/m^2 in January. During the warmer months, cooling energy is needed in July (0,5 kWh/m^2) and August (0,9 kWh/m^2). In Abdullah's building, cooling or heating are needed throughout the year. Heating might be required between November and April and the heating demand, while reaching 1,6 kWh/m^2 in January, ranges between 0,1 and 0,3 kWh/m^2 the other cold months. Cooling energy is needed between March and November. During these months, the monthly demand stays below 1 kWh/m^2 in March, April and November. It reaches 3,2 kWh/m^2 in May, 6,4 kWh/m^2 in June, 9,5 kWh/m^2 in July, peaks at 10,4 kWh/m^2 in August, and decreases to 4,7 kWh/m^2 in September, and to 1,6 kWh/m^2 in October.

While we had a general view of the energy demand for heating and cooling Manzil Zaynab Khatun, in figure 5.20, results obtained by looking at different interior spaces are summarised. The ground floor (348 m^2) has a heating demand between November and March. In November and March, heating demand is around 0,3 kWh/m^2; in December is about 1,4 kWh/m^2; in January, it peaks at 5,7 kWh/m^2, and in February decreases to 1,6 kWh/m^2. The cooling demand of the same floor reaches the following values (kWh/m^2): 0,3 in May, 1,8 in June, 3,5 in July, 4,5 in August (peak), 0,9 in September and 0,1 in October. To maintain comfortable temperatures in the 107 m^2 central hall (East), the following demand needs to be covered for heating (kWh/m^2): 0,4 in December, 2,9 in January (peak), 0,2 in February. In summer, while cooling might be needed from May to October, the months in which the cooling demand is the highest are June (8,4 kWh/m^2), July (16,6 kWh/m^2) and August (19,2 kWh/m^2). The last space simulated, a room on the third floor (North) measuring 16 m^2, show a heating demand only during December (0,1 kWh/m^2) and January (1,0 kWh/m^2). The room appears to be the only simulated space that has a cooling demand from April to October. From April to May, the monthly energy demand reaches 0,3 kWh/m^2 and 2,8 kWh/m^2, respectively. The following months reach their peak with 12,0 kWh/m^2 in June, 20,1 kWh/m^2 in July, and 23,7 kWh/m^2 in August, decreasing to 10,2 kWh/m^2 in September and 2,6 kWh/m^2 in October. As it is possible to be observed in the yearly results, cooling demand increases in the top floors, while heating demand is higher on the lower floor.

The results obtained for the heating and cooling demand of Abdullah's building have been summarised in figure 5.21 to observe differences between the ground floor (55 m^2), the second floor (75 m^2) and the upper floor, the fourth (78 m^2). On the ground floor, energy demand for heating is needed from November to April. Most of the winter months heating demand is between 0,1-0,3 kWh/m^2, while in January reaches 1,9 kWh/m^2. Cooling demand is needed only during July (0,3 kWh/m^2) and August (0,9 kWh/m^2). There is no need to heat or cool during the remaining months (May, June, September, and October).

On the second floor, every month has an energy demand coming from heating or cooling. Heating demand needs to be covered from November to March. While for most of the months the demand ranges from 0,1-0,4 kWh/m^2, in January, it peaks at 1,9 kWh/m^2. Cooling is needed throughout the months between April and October. The peaking months for cooling are June (2,3 kWh/m^2), July (5,3 kWh/m^2), and August (6,5 kWh/m^2).

The fourth floor has energy demand for heating or cooling during the whole year. The energy demand for heating needs to be covered between November and March and peaks at 1,1 kWh/m^2 in January. Between February and November, the floor needs to be cooled down. The summer months in which the colling demand is higher are the following: 13,6 kWh/m^2 in May, 24,4 kWh/m^2 in June, 32,0 kWh/m^2 in July, 33,2 kWh/m^2 in August (peak), and 17,4 kWh/m^2 in September. As it happened with Manzil Zaynab results, the higher the floor, the higher the cooling demand.

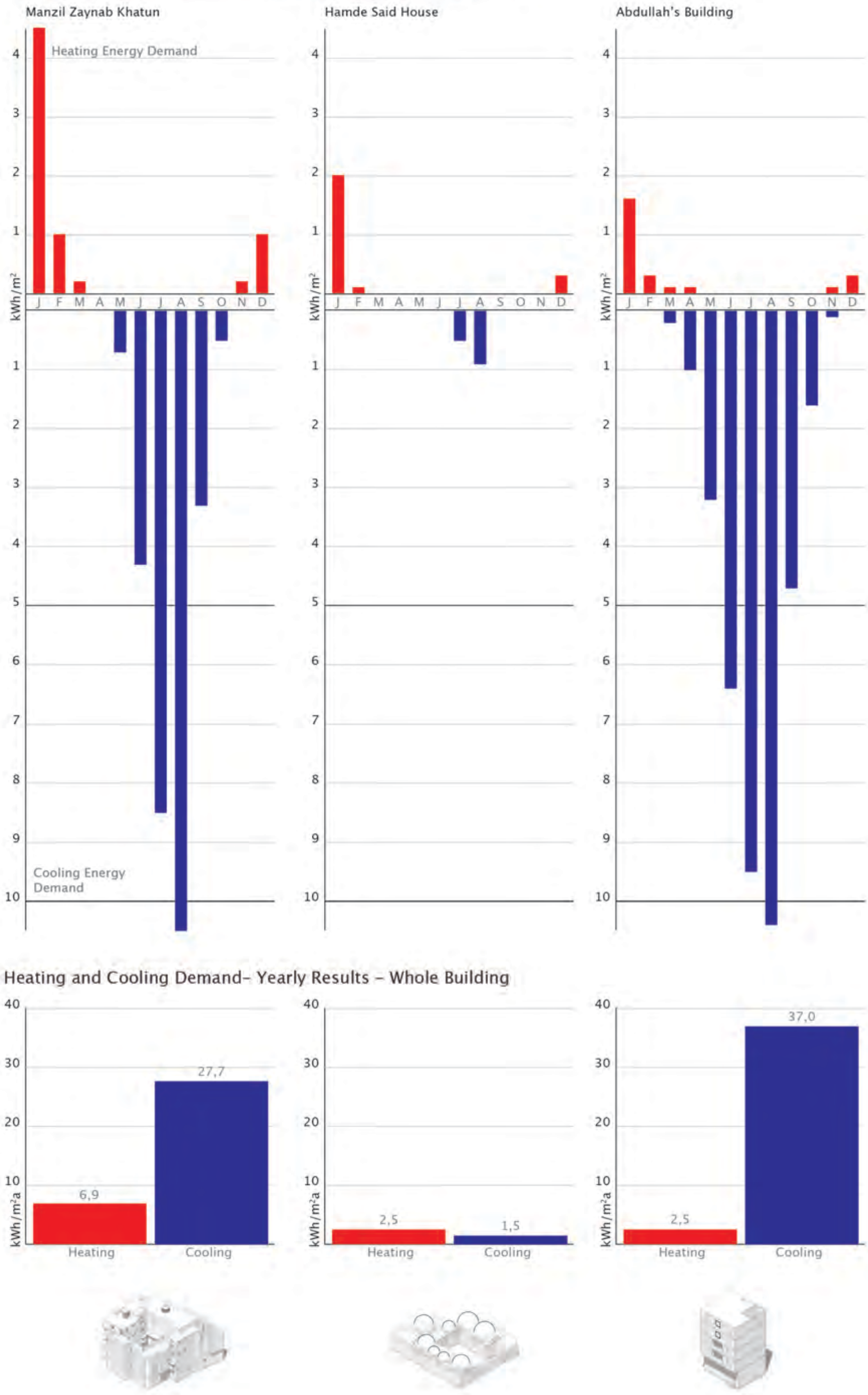


Figure 5.19 – Heating and cooling demand of the three buildings – Monthly results.

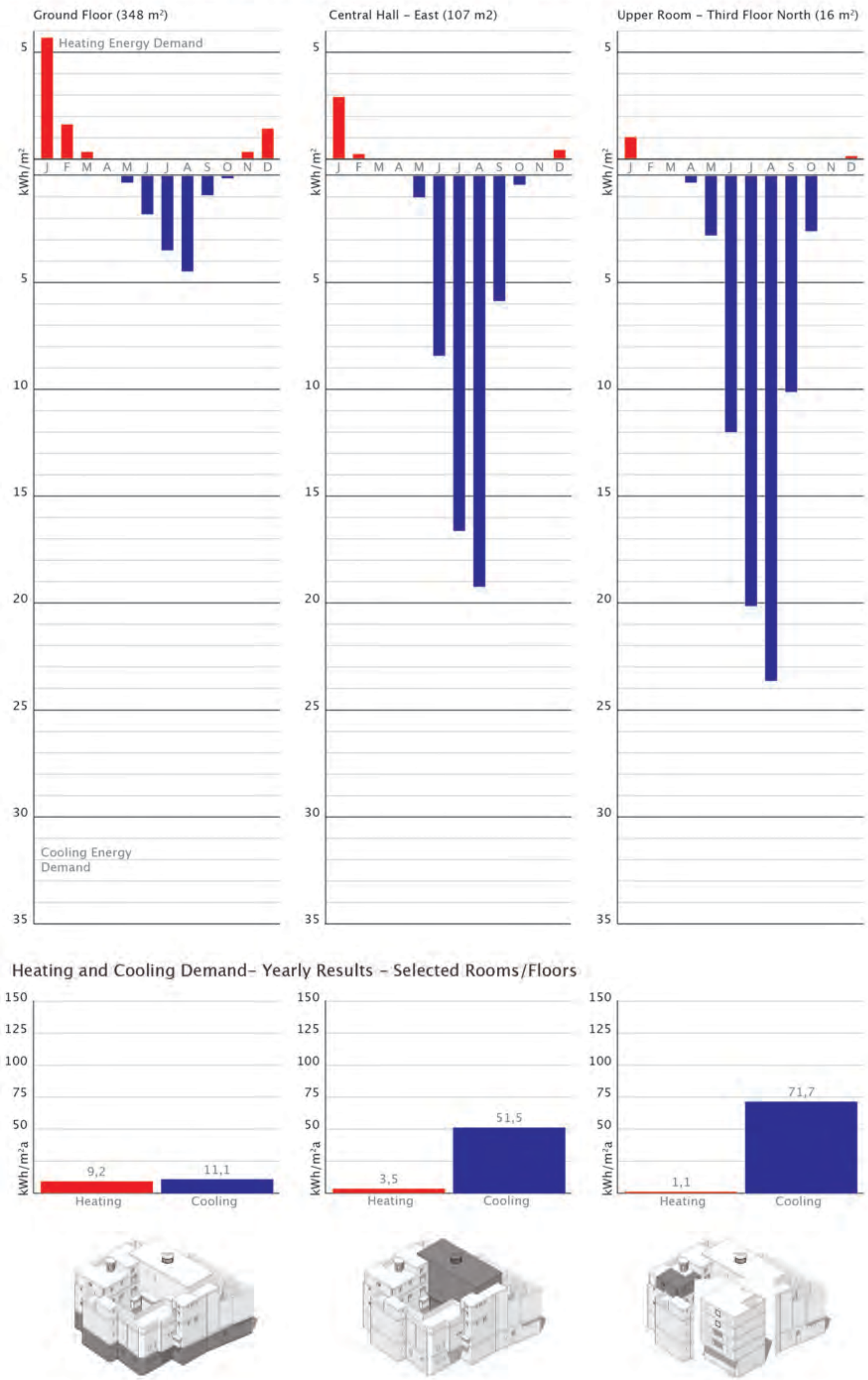


Figure 5.20 – Heating and cooling demand of Manzil Zainab Khatun – Monthly results (Ground Floor / Central Hall East / Third Floor North).

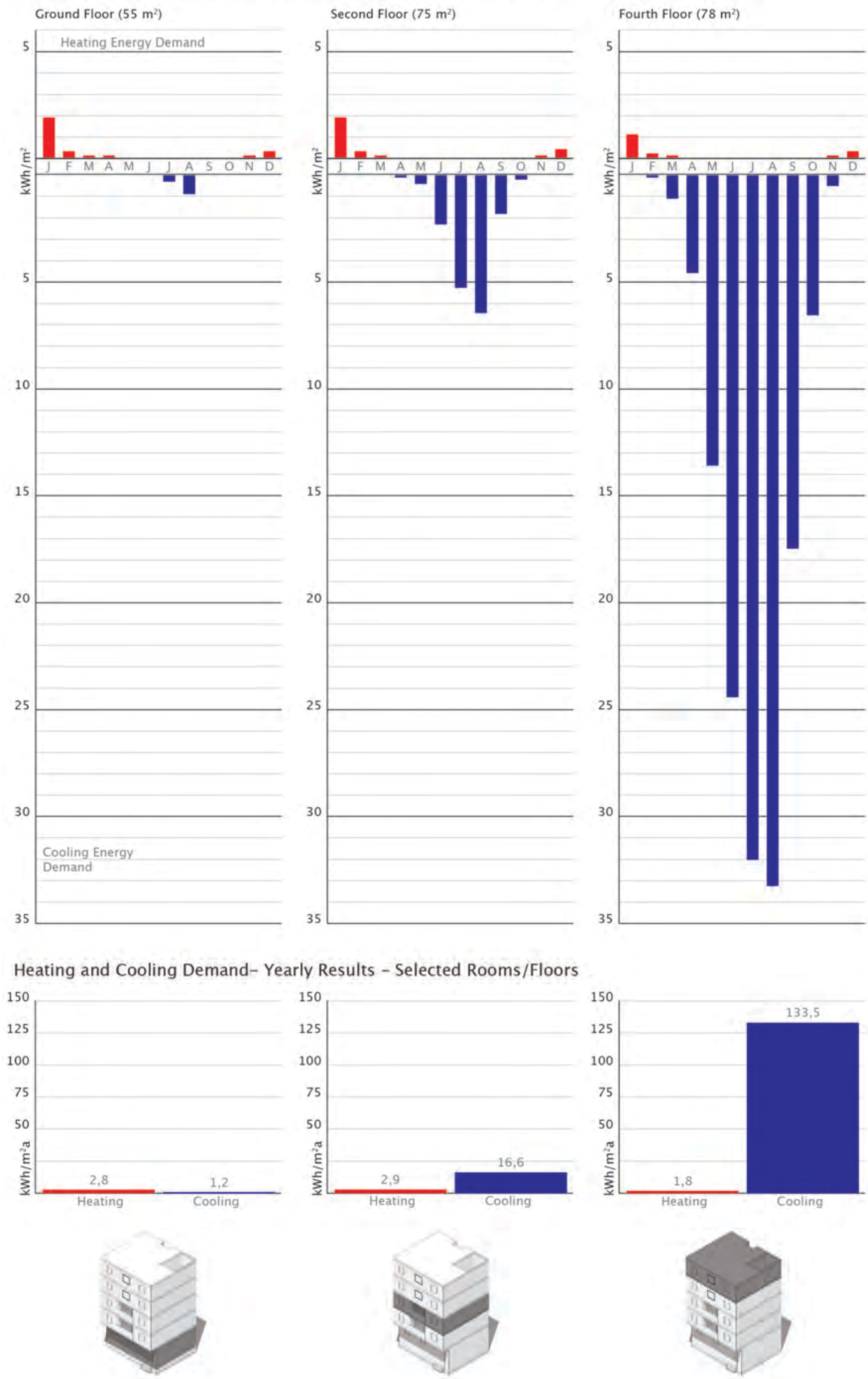


Figure 5.21– Heating and cooling demand of Abdullah's Building – Monthly results (Ground Floor / Second Floor / Fourth Floor).

Table 5.6 – Sensitivity analysis test runs, output.

Variable	Value	Zaynab Khatun		Hamed Said			Abdullah's			
		Test 01	Test 02	Test 01	Test 02	Test 03	Test 01	Test 02	Test 03	Test 04
External wall	SRC	**0,894**	**0,932**	**0,864**	**0,741**	**0,868**	**0,629**	**0,618**	**0,618**	**0,631**
	P	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Flat roof	SRC	**0,322**	**0,282**	**0,499**	**0,499**	**0,561**	**0,438**	**0,459**	**0,487**	**0,543**
	P	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Partition construction	SRC	**0,030**	**0,019**	**0,055**	-	-	**0,206**	**0,287**	**0,321**	**0,234**
	P	0,057	0,571	0,056	-	-	0,014	0,000	0,000	0,000
Local shading	SRC	**0,132**	**0,092**	**0,005**	-	-	**0,149**	**0,287**	-	-
	P	0,003	0,003	0,860	-	-	0,073	0,146	-	-
Natural Vent. Rate	SRC	**0,006**	**0,005**	**0,055**	-	-	**0,139**	-	-	-
	P	0,848	0,879	0,049	-	-	0,077	-	-	-
Ventilation Setpoint	SRC	0,030	-	**0,055**	**0,004**	-	**0,084**	-	-	-
	P	0,370	-	0,049	0,923	-	0,267	-	-	-
Glazing	SRC	-	-	-	**0,084**	**0,009**	-	-	-	-
	P	-	-	-	0,026	0,915	-	-	-	-
WWR	SRC	-	-	-	**0,018**	-	-	-	-	-
	P	-	-	-	0,628	-	-	-	-	-
ADJUSTED R SQUARED VALUE		**0,9391**	**0,9541**	**0,843**	**0,849**	**0,864**	**0,616**	**0,643**	**0,659**	**0,721**
BEST RESULTS										
AIM		ASHRAE 55 Adaptive 90%					CEN 15251 Cat III			
Legend: U=U-Value; SRC=Standard Regression Coefficient; P=P Value; Importance:								High	Med.	Low

5.2.2.4. Sensitivity Analysis

As explained in the methodology introduction, the last part of simulations aims to identify the design variables that have the greatest and least impact on comfortable operative temperatures. Each model is unique; therefore, the results obtained and the confidence vary from test to test. Surely enough, each result needs to be assessed, keeping in mind some variables that cannot be computed.

With Manzil Zaynab Khatun, it was possible to reach high confidence on the input variables already after two test runs (see table 5.6, adjusted R^2 value=0,954). In this case, comfort is most strongly influenced by external wall construction (SRC=0,932), by flat roof construction (SRC=0,282), and moderately influenced by local shading type (SRC=0,092). Partition construction and natural ventilation rate, as shown in the first test, do not have a notable influence on comfort. When looking at the analysed variables, minimising conductive heat flow and solar gains, as well as the interception of solar gains, seems to be the design strategies that are most suitable for this building.

The three sensibility analysis runs for Hamed Said house show results that might be accepted with medium-high confidence (adjusted R^2 value=0,864). Comfort is most strongly influenced by external wall construction (SRC=0,868) and also strongly influenced by flat roof construction (SRC=0,561). The input and output are directly related, and the glazing template does not have a notable influence on comfort. In the first analysis with six variables, low sensitivity is found for internal partitions, local shading, natural ventilation rate and ventilation setpoint. In the second run, where all high p-value options (apart from ventilation setpoint) are ignored, two new variables are introduced (glazing and WWR). The adjusted R squared value remains similar to the first test. This sequence of tests suggests that in this case, minimising conductive heat flow and solar gains has more impact on comfort than the promotion of ventilation or interception of solar gains. The (small) windows are placed inside, and behind a thick wall might support the idea that overhangs would be superfluous.

The four sensibility analysis runs for Abdullah's building show a result that can be accepted with medium confidence (adjusted R^2 value=0,721). Comfort is most strongly influenced by external wall construction (SRC=0,631), and it is also strongly influenced by flat roof construction (SRC=0,543) and partition construction (SRC=0,234). Especially this last point is quite interesting: Abdullah's is the only building of the three without load-bearing walls. When looking at the first test results, in which six variables were computed, we find higher p-values resulting from local shading, ventilation setpoint, and glazing. This indicates that they are not significant in the presence of the others (therefore were removed from future tests). Tests 03 and 04 have been done using the same variables, but the geometry has been modified in the latter one. Medium confidence means that there might be other variables that can influence the results. For the fourth test, because the staircase opening on the roof might have been negatively influencing the sensitivity analysis, it has been assumed that the roof is completely closed. And this is how the R squared value increases from 0,659 (test 03) to 0,721 (test 04). Another important factor that might play against these three variables, which this kind of analysis cannot recognise, is that Abdullah's building is embedded between three adjacent buildings (plus an opposite one). That might suggest that, in this case, thermal mass (and minimising conductive heat flow) plays a bigger role than openings and ventilation.

5.2.3. Summary of Results

By looking at the summary of the thermal and energy demand analysis (table 5.7), the different aspects analysed previously start showing a detailed picture of each building. Starting with one end of the spectrum, Hamed Said house, we have seen that the average T_O of the building, as well as the results gained by its single zones, show constant temperatures within or near Givoni's *Boundaries of Acceptable Conditions for Still Air* throughout the year. During the colder days, the temperature of its rooms varies between 17-19°C, and the building needs an average of 2,5 kWh/m² to bring T_O in the comfort zone between December to February. During the hot summer days (in which T_{OUT} can reach 38°C), operative temperatures remain constant within the 28-30°C range. Extreme temperatures (> 33°C) were not recorded, and to decrease T_O during the 105 yearly hours in which temperatures are above 29°C, a cooling demand of 1,5 kWh/m² must be met. Especially in summer, it seems that night ventilation (in the analysed room, with about 3-4 ac/h) can help dissipate some of the solar gains. Sensitivity analysis has confirmed that minimising conductive heat flow and solar gains has more impact on comfort than the promotion of ventilation or interception of solar gains.

On the other end of the performance spectrum, we have the other two buildings, that although they share a similar behaviour when comparing T_O, have a wider range of results. During the colder days, Manzil Zaynab Khatun, with temperatures ranging between 15-19°C, accounts for 1.170 hours (per year) below 18°C, which need to be compensated with 6,9 kWh/m² of heating energy. During the same period, Abdullah's building, with temperatures ranging between 14-19°C, reaches temperatures below 18°C for 625 hours. Although this is the lowest number between the three buildings, 2,5 kWh/m² are needed yearly to heat the spaces. Sensitivity analysis shows with high confidence that during August, comfort is most impacted by minimising conductive heat flow and solar gains (with low U-values for walls and roof construction). In addition, the interception of solar gains with the use of window overhangs is moderately influencing the results.

Table 5.7 – Summary of results.

	Indicator	Manzil Zaynab Khatun	Hamed Said House	Abdullah's Building
Average Building T_O	**Monthly Results**	Lowest average temp in winter months	Lowest ΔT fluctuation	Average temperature always higher than other two buildings
	Winter and Summer Weeks	Reacting fast to T_{OUT}	Best perfomance: most comfortable thermal conditions	Performing well in winter, and very bad in summer
Thermal Gains and Ventilation (3 rooms)	**Winter Days**	Biggest source of heat gains in all three rooms come from solar gains.		
	Summer Days	Thanks to a clever ventilation strategy, the effects of daily solar gains can be partially reduced with natural ventilation and internal air movement		
		Nat Vent 10-11 ac/h	Nat Vent 03-04 ac/h	Nat Vent 7-8 ac/h
Hourly Temperatures Results	**Winter Day**	Temperatures between 15-19°C (GF the coldest, highest floor warmest)	Temperatures between 17-19°C (coldest part being the studio near the loggia)	Temperatures between 14-19°C (western rooms being always colder than eastern rooms)
	Summer Day	Temperatures between 28-36°C (the higher, the warmer)	Temperatures between 28-30°C	Temperatures between 28-37°C (the higher, the warmer)
	Yearly Temperatures below 18°	1170 hours	852 hours	625 hours
	YearlyTemperatures above 29°C	1135 hour (2.598 in the third floor)	105 hours	1117 hours (3.169 in the fourth floor)
	Temperature above 33°C	153 hours Third floor, August)	0 hours	326 hours Fourth floor, August)
Energy Demand	**Heating**	6,9 kWh/m^2 (November to March)	2,5 kWh/m^2 (December to February)	2,5 kWh/m^2 (November to April)
	Cooling	27,7 kWh/m^2 (May to October)	1,5 kWh/m^2 (July and August)	37 kWh/m^2 (March to November)
Sensitivity Analisys	**R Squared, Confidence, and variables influencing comfort the most**	R2 = 0,954 High confidence 1. External wall 2. Flat roof 3. Local shading	R2 = 0,864 Med.-high confidence 1. External wall 2. Flat roof	R2 = 0,721 Medium confidence 1. External wall 2. Flat roof 3. Internal partitions

During the warmer days, even though we have found in both buildings similar building average results for the number of hours with $T_O > 29°C$ (about 1.125 hours), we can see that especially in the higher storeys, these number may double (Manzil Zaynab Khatun) or even triple (Abdullah's building). When looking at the detailed room results, and especially at the number of hours in which $T_O > 33°C$, we can also see that the single rooms in the higher floors, to be precise, the rooms just under the roof, can reach 153 hours per month (Manzil Zaynab Khatun) and 326 hours per month (Abdullah's building). And this also happens with a relatively high number of air-change per hour (when possible). Although both buildings have a relatively high cooling demand, Manzil Zaynab Khatun has a cooling demand only between May and October (27,7 kWh/m^2) and Abdullah's building need to be cooled for a more extended period (from March to November – cooling demand of 37 kWh/m^2). The sensitivity analysis done for this building shows only medium confidence, which means that other variables might also influence comfort levels. Nevertheless, while also in this case it seems that walls and roof construction influence user's comfort strongly, internal walls play a significant role also, helping in minimising conductive heat flow.

5.3. General Discussion

In the first part of this chapter, we dug into the definition of vernacular architecture. While realising that informal dwellings might also be considered (contemporary-) vernacular, we understood the history, vocabulary, design strategies and passive systems used in three Cairene buildings. In the second part of the chapter, we assessed the thermal and energy performance of the three buildings with the help of Building Performance Simulation Software. While the theoretical approach might have led us to think that the two older buildings might have a better performance than the informal one, we realised that it might not always be the case by using the empirical method.

By immersing in the theoretical study of Manzil Zaynab Khatun, we realised that the building features most of the available passive systems and design strategies to cope with the Cairene climate. The orientation of the building and the use of compact volumes around a central courtyard, the inclusion of the loggia, the extensive use of mashrabiya, the lantern, the height of the rooms and the use of massive and load-bearing construction are only some of the main characteristics that made it possible to its dwellers, to be comfortable most of the year. Another aspect that must be mentioned again is the flexibility of the spaces: the private parts of the house (above the ground level) had several rooms and areas that were utilised depending on the seasonal circumstances (e.g. the use of the roof for sleeping during hot summer nights). By looking at the results of the performance tests, we find in Manzil Zaynab Khatun, a building that, especially on the higher floors, suffers from high temperatures (in summer). Nevertheless, we know that there is still some uncertainty, especially in consideration of the input given to the model. By modelling Manzil Zaynab Khatun, it was not possible, for example, to get into more details and simulate the stack effect in the bigger rooms or associated with the courtyard, or the actual impact that mashrabiya have on the air temperatures and humidity. So at least for this building, which is the most complex of the three in terms of geometry and volumes, we are pretty confident that while we kept a more conservative view (worst case) in the simulations, the performance in the "real world" might be better (also see Mousa, 2016).

In the study of Hamed Said house, we went through the history of its construction. We gained the impression that the architect, by taking desert architecture as a primary inspirational source, has been able to re-interpret its features in a "modern" context while benefiting from the internal thermal comfort and cost-effectiveness. This country house does not have all the features seen in the older building. Nevertheless, it seems that the few passive systems used (e.g. small windows, high thermal mass, high-domed ceilings, the possibility to cross-ventilate, greenery in the courtyard and around the house) might be more than enough to achieve an excellent thermal performance all year round. The simulations result confirms that.

In the theoretical part of the chapter, by describing Abdullah’s building, although we also generalised some points to give a broader picture of informal buildings, we have realised that economical use of space and construction materials is the biggest constraint and most crucial factor in such project. In this dwelling, not much is left when considering elements taken from traditional buildings (e.g. the courtyard has been re-dimensioned and transformed in a shaft). Nevertheless, by considering the densely-built context, we realised (also before the simulations) that ventilation might be a severe problem in such conditions. The simulations show clearly that this building is the less performing of the three in terms of energy and thermal performance. In summer, especially the higher floors can reach operative temperatures above 33°C for more extended periods. Although these results might seem apparent and expected, there is some uncertainty because the building is embedded in a high dense built context. While we think this might positively impact the performance in summer and winter (higher heat capacity, interception of solar gains, minimising heat flows), further analysis should be carried out to understand the matter thoroughly.

As already mentioned previously, buildings are complex systems, and the variables involved in understanding the consequence of a single passive system on the whole building might be complicated. However, in this work, we have been able to identify systems and strategies used in the Egyptian metropolis. To some extent, we pointed out some of the critical factors that impact the most comfort and energy performance in these three buildings. In the next chapter, we will take all this knowledge as a basis for discussion. Again, with the help of Building Performance Simulation Software, we will focus on the optimisation of Abdullah's building. While trying to increase its thermal performance and lower the energy demand, we will see to what extent it is possible to optimise the building only by using passive systems. Furthermore, we will dig into the economic implications that such optimisation might bring and the impact that design decisions might have concerning a changing climate.

6. Towards the New Vernacular

With the lesson learnt in the fifth chapter, this is part of the work aims to reflect on the traditional principles that might be transferred in contemporary informal buildings and conduct an optimisation study based on Abdullah's building. Different strategies, systems, and options to increase comfort and decrease energy demand in the building are explored. In addition, some of the well-performing options are further analysed, and through a cost-benefit and a future climate scenario analysis, the consequences of their implementation are discussed. At the end of this analysis, it becomes clear what affects Abdullah's building performance and which measures might be taken to tackle the issues partially. Suggestions for retrofitting the building are given. Moreover, a study showing Abdullah's building performance in different urban settings is carried out to find which systems and strategies might affect end-user comfort in different urban situations. While this last point also evidences the influence of the context on informal buildings, it leads us to a series of recommendations that might be useful either when designing a new building or when trying to retrofit an existing one.

6.1. Transferability of Strategies and Systems

As we have seen previously, the analysed buildings were built using all possibilities at disposal to comfort their inhabitants. While we have discussed that Hamed Said is well-performing in such a climate, an informal building like Abdullah's finds its limits in comforting its dwellers, especially on warm summer days. So, the question arises: *which strategies and systems used in the past might be transferred to an informal building to optimise thermal and energy performance?*

When taking Abdullah's building and its footprint as an example, and while keeping in mind that we cannot influence external factors (e.g. solar and wind orientation), there are at least two approaches to transfer strategies and design: the first one is by focusing on techniques that can be applied without modifying the geometry of the building, and therefore, without compromising the distribution of space: minimising solar gains (e.g. small WWR), minimising conductive heat flow (e.g. insulated roof, high thermal mass), intercepting and reflecting solar gains (e.g. overhang and shutters, light coloured roof).

In addition to these strategies, another approach would be modifying the distribution of spaces and creating a geometry in which ventilation is promoted as much as in the older examples. (For example, adding double-height rooms and increasing the size of the ventilation duct would increase stack effect, allying internal and external openings would increase natural cross ventilation). In this case, it is essential to consider that some of the passive systems used in traditional buildings, especially those promoting ventilation, are space-consuming (e.g. courtyard, lantern, windcatcher). Therefore, their application in a dense context such as Abdullah's, which is defined as "premium local land" (because of being a small plot, infill, and hidden within the built fabric), and characterised by very economical use of space, might not be possible without compromising the living area spaces (Sims, 2012, p. 126).

Table 6.1 – Passive systems and design strategies - Applicability to informal buildings. *AB-StatusQuo* represents the actual state of construction; *AB-OP01* represents the optimisation of building elements without changing geometry and surface area for distribution and shafts; *AB-OP02* represents the range of systems available when building geometry, and surface area for distribution and shafts, are modified. Adapted from Roaf et al. (2005, p. 201).

Passive System	Design Strategy	AB-StatusQuo	AB-OP01	AB-OP02
Solar Orientation	Minimize Solar Gains	-	-	-
Compact Volume	Minimize Solar Gains	●	●	●
Small windows	Minimize Solar Gains	●	●	●
Insulated Roof	Minimize Solar Gains / Minimize Conductive Heat Flow	-	●	●
Thermal Mass	Minimize Conductive Heat Flow	○	●	●
External shade (e.g. , mashrabiya, overhang)	Interception of Solar Gains	○	●	●
Shading by Agglomerate of Volumes	Interception of Solar Gains	●	●	●
Shaded from West Sun	Interception of Solar Gains	●	●	●
Shutters	Interception of Solar Gains	-	●	●
Planting	Interception of Solar Gains / Promote evaporation	-	-	-
Wind Orientation	Promote ventilation	-	-	-
Verandas/Colonnades	Promote ventilation	-	-	●
Cross-Ventilation	Promote ventilation	-	-	●
Stack Cooling	Promote ventilation	-	-	●
Stack Warming	Promote ventilation	-	-	●
Lantern / Ventilation Ducts	Promote ventilation	●	●	●
Wind Catcher	Promote ventilation	-	-	-
Earth Cooling	Promote ventilation	-	-	-
High rooms	Promote ventilation	-	-	●
Pools/Evaporation	Promote evaporation	-	-	-
Summer/Winter Rooms	Adaptation	-	-	-
Courtyard	Promote radiant cooling	-	-	-
Light Coloured Roof	Reflection of Solar Gains	●	●	●
Legend: in grey = external influence // ● = yes ; ○ = partially available ; - = not available				

Table 6.1 displays the list of systems and strategies and their possible application to an informal building depending on the chosen approach. For the continuation of this chapter, we will focus on optimisation by using a more conservative approach (AB-OP01), and therefore we will not compromise the geometry of the digital model. Nevertheless, knowing that options might be limitless when it comes to design variants, we realise that further investigations should be undertaken to analyse opportunities in which space is allocated to promote ventilation strategies.

6.2. Optimisation Study of Abdullah's Building

6.2.1. Introduction and preliminary Sensitivity Analysis (SA) Results

This section aims to find out the possibilities for optimising the thermal comfort of Abdullah's building by using supplementary strategies and determining at what cost (in terms of construction costs and embedded CO_2) such options might be implemented. While the digital model used for the calculations in the previous chapter is used, for this process, a new list of practical options for optimisation is created by following the Egyptian market offer. Because the chosen method focuses strongly on minimising solar gains, minimising conductive heat flow, and the interception of solar gains, and generally speaking, on optimising the envelope and its heat mass) a catalogue of construction materials that can be found in Cairo was redacted and used for the optimisation process. Table 6.2 summarises the variants, settings, and characteristics of each option used[24].

Each phase of a building life cycle (manufacturing and transporting, construction, occupation and renovation, upcycling or demolition) is characterised by different costs, being monetary or environmental (Chou & Yeh, 2015). The monetary costs included in this analysis are limited to the construction costs. They include superstructure costs (roof construction, external and internal walls, ground floor and internal slabs, internal doors) and glazing costs (windows, local shading). The costs excluded are: lighting costs, sub-structure costs, surface finish costs. Material and construction costs have been extrapolated either from official statistics (such as Central Agency for Public Mobilization & Statistics, 2021) or based on recent research work done in Egypt (Abdellatif, 2018; Abouaiana, 2021; Ali, Yehia, & El-Didamony, 2017). The environmental costs considered here are limited to the embodied energy of the materials (and constructions) used and include material extraction, manufacturing, and transporting activities. The source for this data is the *Inventory of Carbon and Energy* (ICE 3.0) created at the University of Bath (see Jones & Hammond, 2019).

As we have discussed in the second chapter, in the DesignBuilder environment, it is possible to conduct a multi-objective optimisation. Therefore, optimal design solutions can be calculated by including different design parameters in combination with two objectives. In our case, the two objectives are: (decrease of) uncomfortable hours, and (decrease of) construction costs. When running the optimisation also other outputs can be summarised. In our case, a secondary output to evaluate the embedded CO_2 of the different solutions is calculated.

To simplify the optimisation study, two sensitivity analyses (SA) are carried out in advance. This is done because an optimisation computed with many variables (ten, in our case) needs a high amount of time[25] to be processed. Furthermore, the results shown might be too complex to be clustered or analysed (Team DesignBuilder, 2021). The first SA aims to explore the variables that have (or do not have) an influence on comfortable hours, while the second one wants to seek the variables in the model that impact the construction costs.

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[24] See also table A.1 in the Appendix for detailed information about thermal properties and material costs (including sources for the latter)

[25] In the example shown in the reference, a model with 12 variables needed 106 hours for an optimisation study (9504 combinations analysed). In contrast, by using SA and Genetic Algorithms, the same study can be done in about 9 hours and by obtaining more evident results (around 1000 combinations tested).

Table 6.2 – Variables and Settings used for Sensibility Analysis and Optimisation.

Variable	DB Name	Material	Thickness d (m)	U-value U (W/m²K)	Cost Estimate Component EGP (EGP / m²)
External Walls (from outside [top] to inside [bottom])	SA_EW_ClayBrick_simple	Brickwork	0,125	2,115	**105**
		Plaster Lightweight	0,013		
	SA_EW_ClayBrick_double	Brickwork	0,125	1,483	**165**
		Air	0,01		
		Brickwork	0,125		
		Plaster Lightweight	0,013		
	SA_EW_ClayBrick_double_EPS	Brickwork	0,125	0,475	**240**
		Air	0,01		
		EPS Expanded Polystyrene (Heavyweight)	0,05		
		Brickwork	0,125		
		Plaster Lightweight	0,013		
	SA_EW_HollowBrick_double	Hollow Clay Brick	0,125	1,540	**185**
		Air	0,01		
		Hollow Clay Brick	0,125		
		Plaster Lightweight	0,013		
	SA_EW_StabilisedSoilBrick_simple (Stabilised Soil Brick = PhD Adobe Wall)	Stabilised Soil Brick	0,125	2,070	**76**
		Plaster Lightweight	0,013		
	SA_EW_StabilisedSoilBrick_double	Stabilised Soil Brick	0,125	1,439	**107**
		Air	0,01		
		Stabilised Soil Brick	0,125		
		Plaster Lightweight	0,013		
Internal Partitions	SA_IP_ClayBrick	Brickwork	0,125	2,166	**60**
	SA_IP_HollowBrick	Hollow Clay Brick	0,125	2,225	**70**
	SA_IP_StabilisedSoilBrick	Stabilised Soil Brick	0,125	2,119	**31**
Roof (from inside [top] to outside [bottom])	SA_ROOF_Basis	Concrete, High density	0,150	2,549	**700**
		Bitumen, felt/sheet	0,020		
		Loose fill/sand	0,050		
		Zement Sand Mörtel	0,025		
		Concrete tiles	0,025		
	SA_ROOF_EPS_50	Concrete, High density	0,150	0,579	**755**
		Cast Concrete	0,050		
		Vapor Barrier	0,005		
		EPS Expanded Polystyrene (Heavyweight)	0,05		
		Concrete tiles	0,025		
	SA_ROOF_EPS_100	Concrete, High density	0,150	0,317	**880**
		Cast Concrete	0,050		
		Vapor Barrier	0,005		
		EPS Expanded Polystyrene (Heavyweight)	0,1		
		Concrete tiles	0,025		
Internal Floors	SA_IF_15	Concrete, High density	0,15	2,985	**525**
	SA_IF_12	Concrete, High density	0,12	3,120	**420**
Ground Floor (from inside [top] to outside [bottom])	SA_GF_Basis	Stone limestone	0,02	1,430	**961**
		Zement Sand Mörtel	0,02		
		Loose fill/sand	0,06		
		Concrete, High density	0,15		
		Clay underfloor	0,5		

Legend: The variables with a grey filling are the ones selected for optimisation

Table 6.2 – Variables and Settings used for Sensibility Analysis and Optimisation (Continuation).

Variable	DB Name	Material	Thickness d (m)	U-value U (W/m²K)	Cost Estimate Component EGP (EGP / m²)
Ground Floor (from inside [top] to outside [bottom])	SA_GF_Ventilated_Traditional	Stone limestone	0,02	1,470	**1100**
		Zement Sand Mörtel	0,02		
		Protection Membrare (Vapor Barrier)	0,005		
		Concrete, High density	0,12		
		Brickwork Slab	0,06		
		Air	0,3		
		Clay underfloor	0,5		
	SA_GF_Igloo_Modern_Insulated	Stone limestone	0,02	0,560	**995**
		Zement Sand Mörtel	0,02		
		Cast Concrete	0,050		
		EPS Expanded Polystyrene (Heavyweight)	0,05		
		Protection Membrare (Vapor Barrier)	0,005		
		Concrete, High density	0,06		
		Air	0,45		
		Concrete, High density	0,05		
Glazing	SA_WIN_Single	Glazing single / Window frame		5,7/3,3	**1750**
	SA_WIN_Double	Glazing souble / Window frame		1,7/3,3	**2200**
	SA_WIN_Triple	Glazing triple / Window frame		1,0/3,3	**4500**
WWR	**Windows to Wall Ratio (5-40%)**	7 steps (min 10; steps every 7,5)			
Local shading	**No Shading / Overhang 1,5 m**	4 steps (0;0,5;1,00;1,5 m)			
Natural Ventilation Rate	**Ventilation rate - Continuos / norm. Distribution**	mean 10 ac/h / stand. Dev. 1			
Ventilation Setpoint	**Ventilation setpoint - Continuos / norm. Distribution**	Mean 20°C / stand. Dev. 1			

Legend: The variables with a grey filling are the ones selected for optimisation

For both analysis, the following variables are included: external walls construction (6 options), internal partitions (3 options), roof construction (3 options), internal floors (3 options), ground floor construction (3 options), glazing (3 options), window to wall ratio (7 steps between 5 and 40%), local shading overhang (4 steps between 0-1,5 meters), natural ventilation rate (mean: 10 ac/h / standard deviation: 1), ventilation setpoint (mean: 20°C / standard deviation: 1).

The SA concerning the comfort hours, done by looking at August, show results that might be accepted with medium confidence (adjusted R^2 value between = 0,7370 and 0,7751). Comfort is most strongly influenced by flat roof construction and is also moderately influenced by glazing template. In the first run of AS, it was found that ground floor construction, local shading type, external wall construction and partition construction, natural ventilation rate, internal floor construction, window to wall and natural ventilation set-point temp do not have a notable influence on comfort. These last results can be explained by the fact that, probably, within the limits of this analysis, the effect of flat roof construction might be too strong (having by far the higher standard regression coefficient of the series). After a second run by excluding the flat roof construction, it was found that comfort is also strongly influenced by ground floor construction, external wall construction and local shading.

The second set of SA show results that might be accepted with medium-high confidence (adjusted R^2 value = 0,882). Total construction cost is most strongly influenced by glazing template and by internal constructions (floors and partitions) and is also moderately influenced

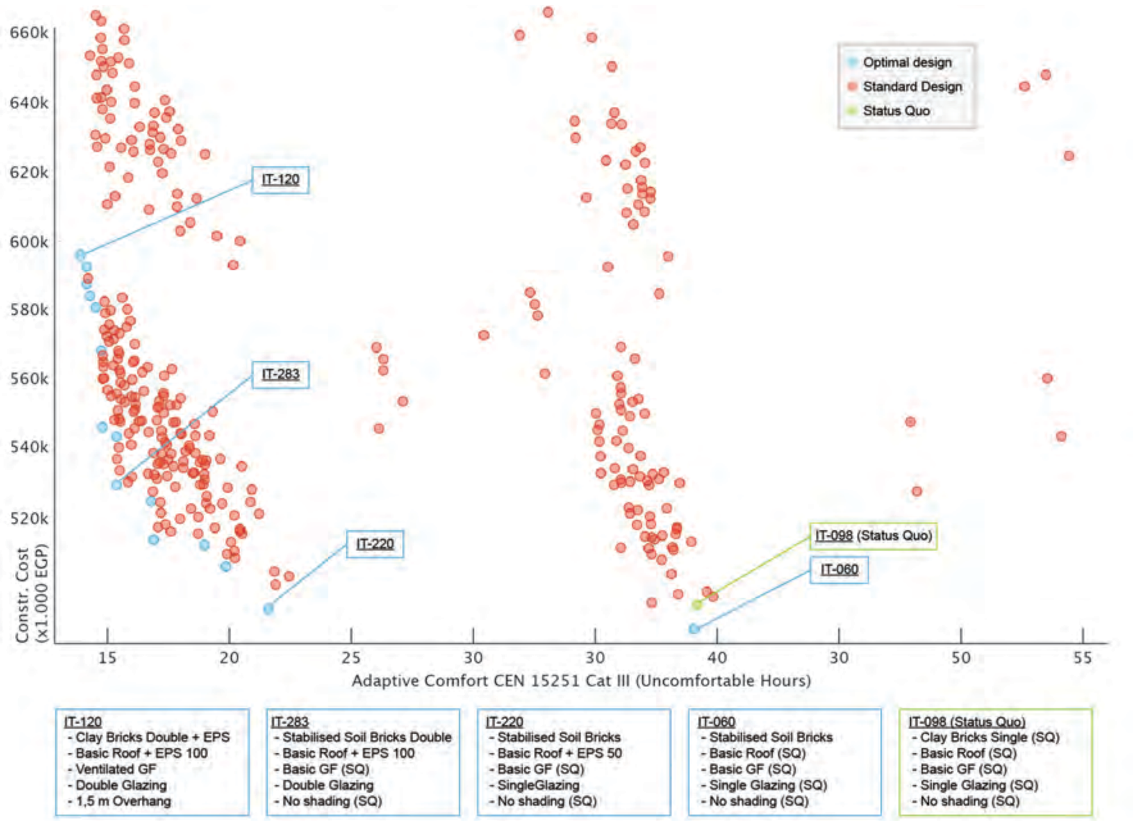

Figure 6.1 – Abdullah's building optimisation results – Comfort and cost – 323 Iterations.

by flat roof construction and external wall construction. Ground floor construction does not have a notable influence on total construction costs. According to these preliminary results, the following variables with a high impact on both aims were chosen for the optimisation study: flat roof construction, external wall construction, ground floor construction, glazing template, and local shading.

6.2.2. Results and Observations

6.2.2.1. Observations Based on the Monetary Costs and Comfort

As we can observe in the different visualisations of the Pareto analysis showing construction *costs and comfort* (figures A.1 - A.4 in the Appendix), there are four major clusters in which the results are grouped and some outlier. The figure in the Appendix might be helping in getting into details; nevertheless, what can be observed for the moment, is that the clusters are impacted significantly by the price and thermal performance of flat roof construction and glazing. Nevertheless, looking at the distribution of construction costs (figure 6.2), higher costs are related to the intermediate floor construction. In figure 6.1, all 323 simulated iterations are visualised, together with the Pareto front and the chosen iterations to be studied in detail.

One of the selected iterations (IT-098) is the simulation representing Abdullah's Building status quo, meaning that both costs and comfort represent the actual situation of the building. As we have already discussed, the options used to construct this iteration are external walls in clay bricks, basic roof construction, basic ground floor, single glazing and no shading. In comparison to the rest of the iterations, this option has a low price (just under 500.000 EGP; see total costs in figure 6.3), as well as a low thermal comfort level (about 38 hours of discomfort in August and

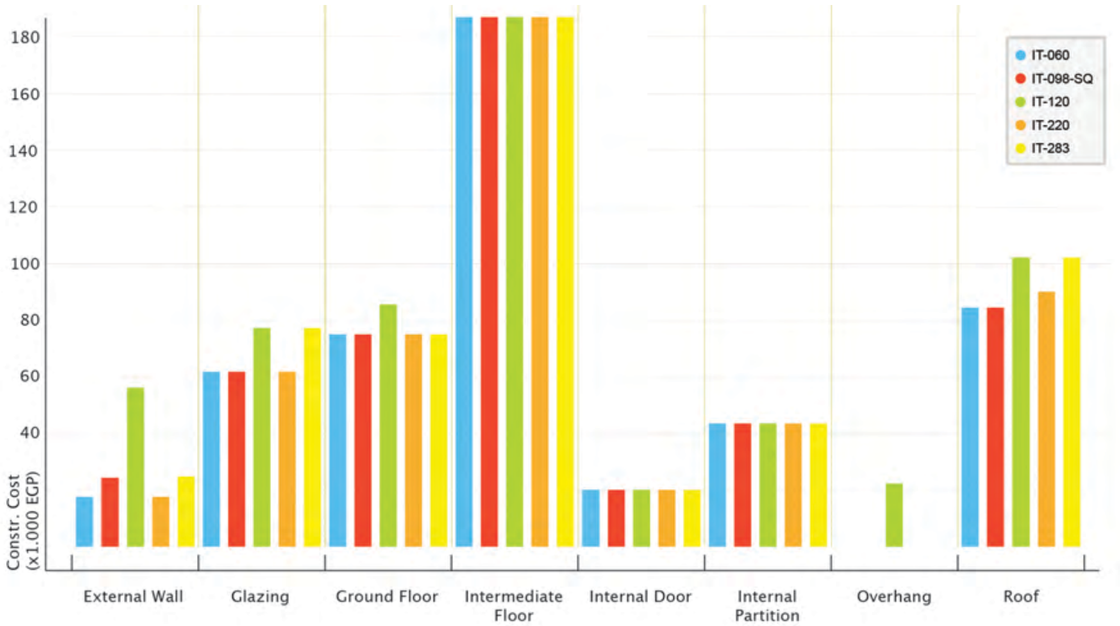

Figure 6.2 – Construction costs of five iterations.

71 per cent of yearly hours between 18-29°C – see also table A.7 in the Appendix). The distribution of costs (figure 6.2) shows that, as in all other iterations, most of the costs are influenced by the concrete intermediate slab (about 186.821 EGP). Both costs for concrete and steel are high; therefore, it is no surprise that this list's second and third positions are filled by roof construction and ground floor. The iteration IT-060, differs from the previous one only in the composition of the external wall construction. With a stabilised soil bricks façade, with 491.000 EGP, this model has a slightly lower cost and a slightly better performance than IT-098.

By going on the better side of performance, IT-220 show a similar price range of the previous iterations (497.000 EGP). Nevertheless, yearly comfort hours (see table 6-3) reach 75 per cent of annual hours between 18-29°C. Besides the basic features of Abdullah's, this model has a layer of stabilised soil bricks used for external walls, and the roof is insulated with 50-millimetre EPS. With the iteration IT-283, we move towards a better thermal performance (83 per cent) and higher construction costs. Here the only options similar to Abdullah's building are the basic ground floor construction and the fact that no shadowing elements are required. The external wall construction is made by a double layer of stabilised soil bricks, the roof includes 100 mm EPS, and the glazing is double.

By including the model IT-120, we include the best thermal performing model of all iterations (88 per cent of yearly hours between 18-29°C) and the most expensive of the Pareto front (596.000 EGP). This model is built with a double layer of compressed soil bricks (with insulation), a high performing roof (100-millimetre EPS), double glazing, and a 1,5 overhang. Although in this work we always put in evidence the optimisation of a building for tackle high temperatures in summer, by looking at the monthly results for comfortable hours (table 6-3), we realise that this is the only option in which optimisation has an influence also during winter months. In the visualisation of the costs, we can see that although this variant has a higher monetary cost than the previous ones, there might be space for optimisation - especially regarding

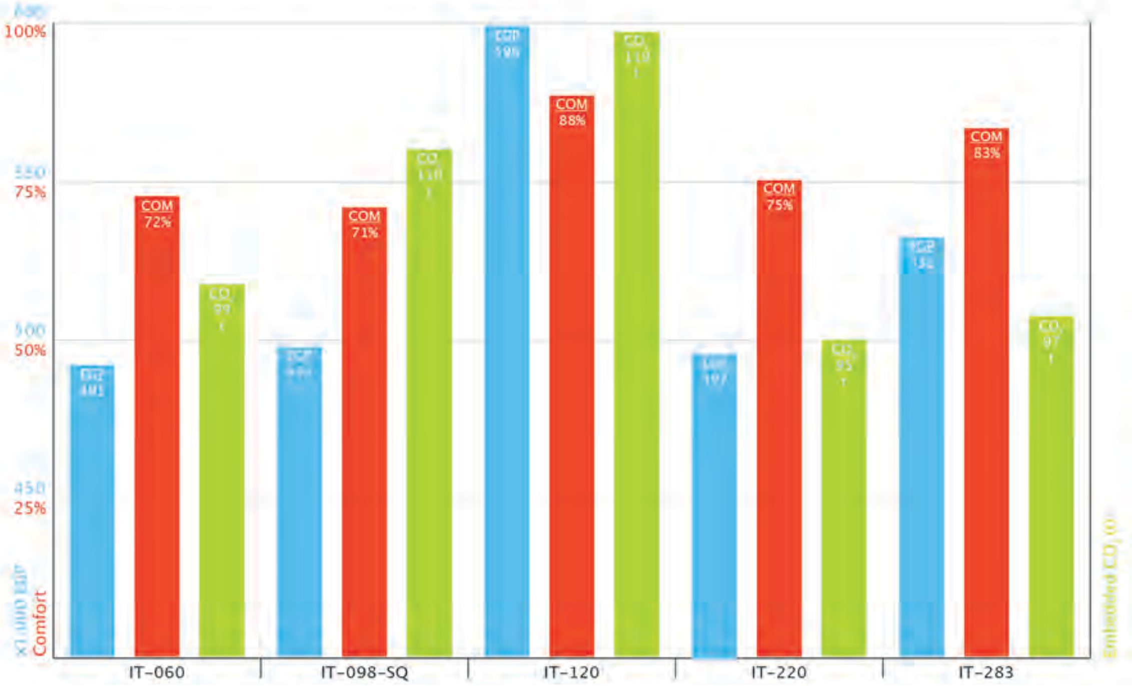

Figure 6.3 – Five iterations: visual summary.

the wall construction. Here the high price is due to clay bricks. Thinking about the use of clay bricks and their costs, it might also be possible to find room for optimisation when looking at the costs of internal partitions. Although we have not included this building in the optimisation study, in this case, it might be interesting to replace this material with stabilised soil bricks that, while being more affordable, have slightly better characteristics for this climate.

A phenomenon that we observed in chapter five is the difference that operative temperatures have in the different floors of the building. Therefore, by comparing the room level, the hourly temperature results of the five iterations have been plotted both for the summer (figure A.9 in Appendix) and the winter week (figure A.10 in Appendix). The room results extrapolated from each iteration are the bedrooms (West) on the ground and fourth floors.

Looking at what happens between the 22nd and the 23rd of January in the fourth-floor rooms, we observe that IT-098 (status quo) and IT-060 have the lowest operative temperatures, around 16°C. With the IT-120, we observe temperatures above 18°C and reaching 19°C. Within this range, we can observe IT-220, with temperatures about 1-1,5°C warmer than the status quo, and IT-283, with temperatures that can be 2°C higher than the status quo. On the lower side of figure A.10 (Appendix), we can observe the bedroom's situation on the ground floor. Here, generally speaking, temperatures swing less than on the fourth floor, and the performance range of the iterations is smaller (<2°C). Nevertheless, the models behave similarly to what was described above. The hourly frequency plotted for the summer week shows IT-098 (status quo) and IT-060 reaching the highest temperatures. If we focus on the fourth floor and look at the highest temperatures on August 19th, we observe that IT-098 and IT-060 reach 36,5°C and the best performing 34,7°C. While all iterations behave between this ca. 2°C range in the hottest hours, during the colder hours, all five iterations range within about 1°C. By observing the ground floor results, in the worst-performing iterations of this series (IT-098, IT-060, IT220), the temperature rises about 1,2 °C during sunny hours, while in the other iterations, it rises about 0,5°C only.

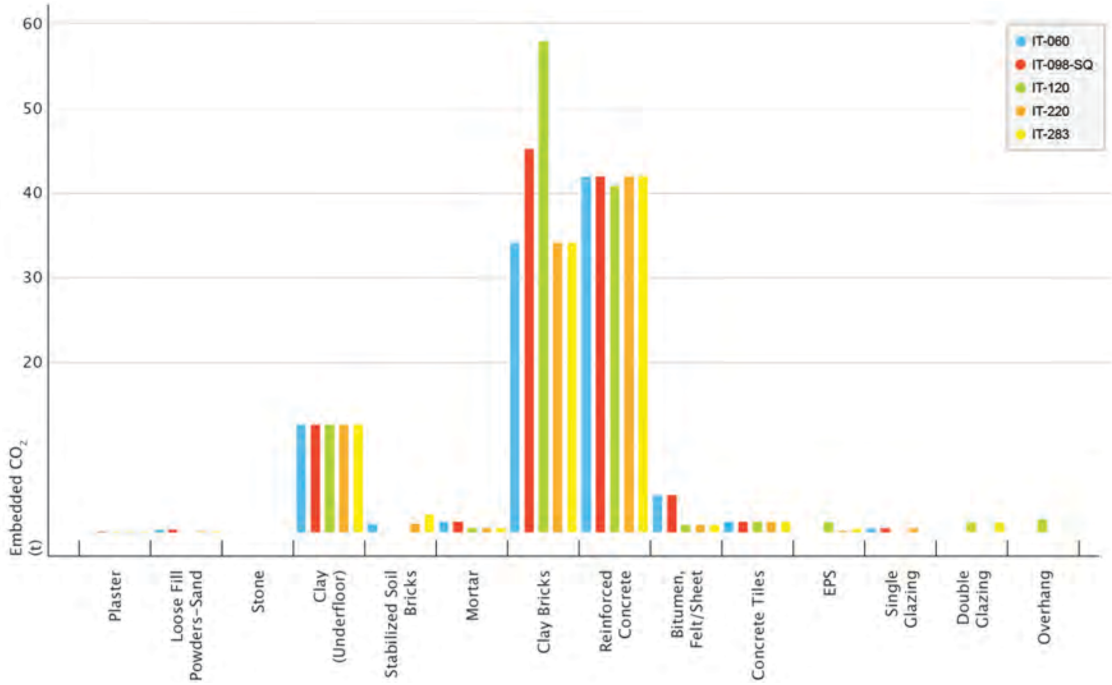

Figure 6.4 – Five iterations: embedded CO_2.

6.2.2.2. Optimisation Based on the Environmental Costs and Comfort

If we look at the output of each iteration related to embedded CO_2, we can observe that each model has a different CO_2 footprint within the range of 95-119 tons. The most thermal performing iteration (IT-120) also has the highest amount of embedded CO_2; the status quo (IT-098-SQ) has about 8 per cent less embedded CO_2, and the other three iterations are all around 97 tons CO_2. Why is that? Figure 6.4, with the listing of embedded CO_2 of all materials needed in the five iterations, might help understand the causes.

The three materials with the highest embedded energy are concrete, brickworks (burnt clay bricks), and clay (used in the underfloor). As we can observe, the quantity of reinforced concrete used in the five iterations is constant at around 42 t CO_2. This is due to its use in all internal slabs and ground floor and roof construction. On average, reinforced concrete slabs (15 centimetres) are used on about 556 square meters and, with a mass of around 200 tons and an embodied carbon mass of 0.21 kgCO2/kg, this result is to be expected. Nevertheless, we also have to add that depending on the amount of steel present in the slabs, the value of the embodied carbon mass could increase to 0,31 kgCO2/kg (see Jones & Hammond, 2019), bringing to a total of about 62 tons the embodied energy of the material in this construction.

As we have seen in the previous section, while in the optimisation we have also worked with stabilised soil bricks for the external walls (235 square meters in total), all five iterations still use clay bricks for the internal partitions. By observing the difference between IT-060 (with external walls made of stabilised bricks) and IT-098-SQ (with outer walls made of clay bricks), we realise that the positive environmental effect of using stabilised soil bricks is lower only by about 20%. By covering a total area of about 730 square meters, the use of clay bricks has such a significant impact on the carbon balance that it overtakes the effects of using a stabilised soil bricks façade. The last impactful material on all five iterations is related to the underfloor construction of the ground floor. Here, between 8-10 per cent of the total embedded CO_2 of the building is condensed because of the high use of clay blocks.

6.3. Optimising Further

Looking at these results, there seems to be room for improvement, especially when thinking about the skeleton structure and the materials used for the concrete construction with bricks infill and their influence on monetary and environmental costs. Other researchers have studied and compared the impact on costs, embodied energy, and thermal comfort, of a skeleton building versus a wall bearing structure in the Egyptian context. Ali et al. found that it might be possible to reduce costs and embodied energy of materials if the typical building skeleton was replaced by a wall bearing construction (2017). Abdrabou et al. came to a similar conclusion by showing that many arguments against its use (safety, longevity, restricted versatility) cannot be justified anymore (2016). Already at the time when Hassan Fathy tested his wall bearing structures, he faced a lot of adversities from politically influencing people that were also firmly rooted in the steel and concrete industry. Today, one of the reasons behind the frequent use of skeleton structures in Egypt is lobbying the building industry (Abdrabou et al., 2016).

So, what about changing the structure of our models? Would that bring positive results? Considering that the compressive strength of stabilised bricks is about half that of clay bricks (45 kg/cm^2 versus 100 kg/cm^2), it might be tricky. Nevertheless, it might be worth a try. With the results gained with the optimisation, we could inform further the design, and with the last experiment in this sense, another model was prepared. By decreasing the use of materials with a high monetary and environmental impact, we observed what might happen. Taking the status quo as basis model, variables have been modified as discussed in the observations of the optimisation study, and the optimum model has been created as it follows:

- External wall: stabilised soil bricks double + EPS
- Glazing template: double
- Flat roof construction: basic roof + EPS 100
- Ground floor construction: basic GF (sand filling instead of clay blocks)
- Internal partitions: stabilised soil bricks (double layer = 25 cm)
- Internal floor: 12 cm concrete
- Shading template: no overhang

By simulating a model with these characteristics, it is possible, with construction costs around EGP 517.000 (+4,4 per cent in comparison to status quo), to have a building in which comfortable temperatures between 18-29°C are reached 91 per cent of the year. Furthermore, thanks to compressed soil bricks and the limited use of concrete, it is possible to reduce the embedded energy to 55 tons (see detailed results in Appendix, table A.8). As we can observe in figures 6.5 and 6.6 by comparing the results of the optimum solution with the status quo (IT-098-SQ) and the (in terms of thermal comfort) best performing model (IT-120), we can observe the following:

- although stabilised soil bricks are responsible for about 10t CO_2, practically all embedded CO_2 related to clay bricks might be removed (between 57-70 t CO_2),
- the embedded CO_2 related to the concrete slab slightly decreases,
- the costs related to the intermediate floor decreases by about 20 per cent,
- roof costs increase by 26 per cent (compared to status quo).

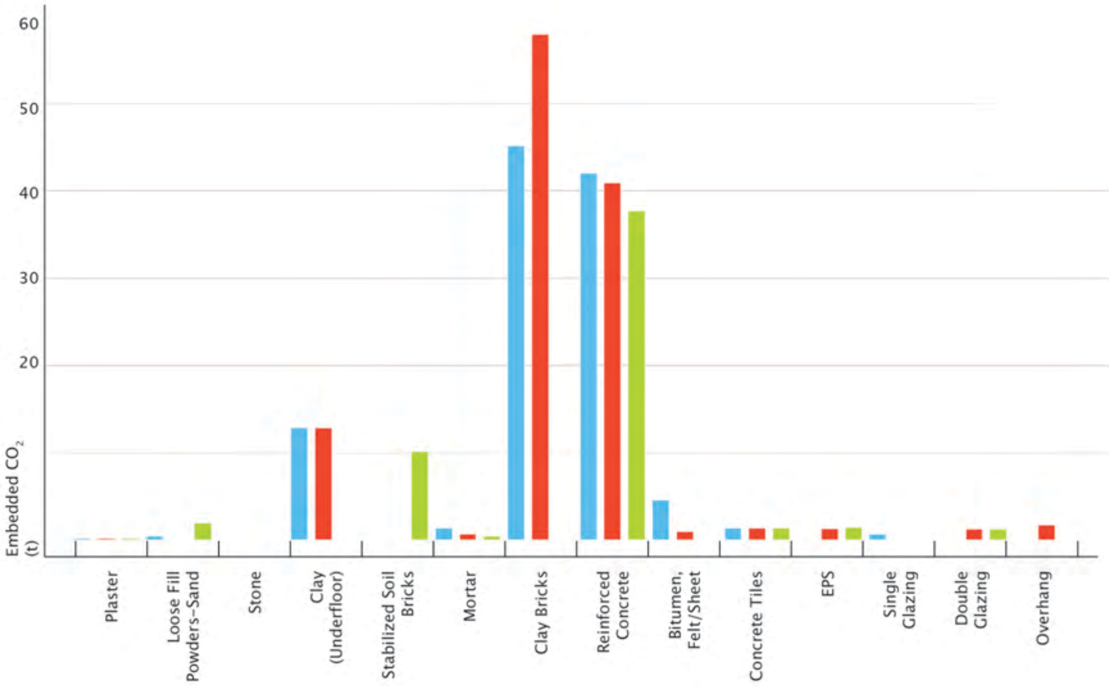

Figure 6.5 – Embedded CO_2 of IT-098-SQ, IT-120, and OPTIMUM.

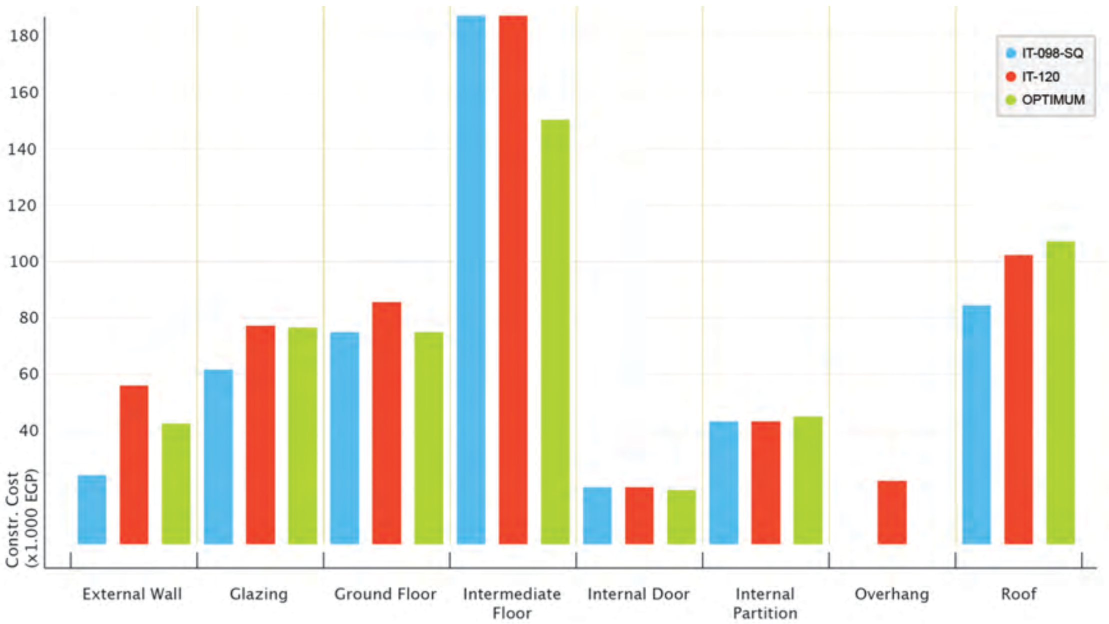

Figure 6.6 – Construction costs of IT-098-SQ, IT-120, and OPTIMUM.

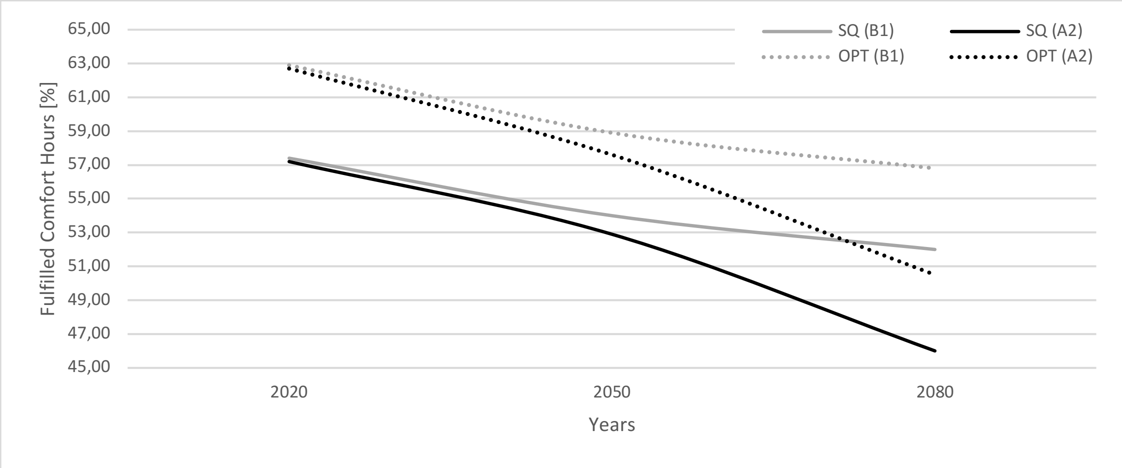

Figure 6.7 – Status Quo and Optimum: fulfilled comfort hours in different climate scenarios.

While it is clear to the author that the optimum model might be adjusted further (e.g. the bearing walls in the ground floor might have to be thicker to sustain the structure) when considering monetary and environmental cost and the building's thermal performance, the option to use a wall bearing system seems to bring many advantages in this kind of context.

6.4. Future Climate Scenario Analysis

At this point, it might be interesting to get an insight into the consequences on the building's thermal comfort that a changing climate and higher temperatures might bring. By following the same procedure seen in chapter 3.4, we took Abdullah's building models (status quo and optimum) to observe how the model perform in different future scenarios, namely:

- Scenario AR4-A2 (business as usual) – year 2020
- Scenario AR4-A2 (business as usual) – year 2050
- Scenario AR4-A2 (business as usual) – year 2080
- Scenario AR4-B1 (best-case) – year 2020
- Scenario AR4-B1 (best-case) – year 2050
- Scenario AR4-B1 (best-case) – year 2080

For this study, instead of also looking at the percentage of monthly comfortable hours between 18-29°C (that would require twelve simulations and a long time in extrapolating the data), a parametric simulation is done (four runs) and assessed by observing the comfortable hours as in the adaptive comfort standard CEN 15251 (Cat II).

Table 6.3 and figure 6.7 summarise the results of the study. Starting with a comparison of the business-as-usual scenario (A2), we can observe that the fulfilled hours of the status quo model performance decreases from 57,2 per cent in 2020 to 46 per cent in 2080. In this case, the percentual lost in comfort is about 11 per cent. Under the same scenario, the optimum model shows a decrease of about 12 per cent during the same period. Nevertheless, in 2020, the fulfilled hours reach 62,7 per cent; in 2080, it is expected to be still better (4.733 hours versus 4.027) than the status quo. Regarding scenario B1 (best-case), the status quo will lose about 5,4 per cent of comfortable hours, reaching a total of 4.553 hours in 2080. The optimum model, also starting in this case with a better performance in 2020 (5.507 hours), will lose about 7 per cent of comfort hours by 2080 (reaching 4.974 fulfilled hours).

Table 6.3 – Status Quo and Optimum: percentage of fulfilled comfort hours in different climate scenarios

Scenario	Year	Status Quo			Optimum		
		Comfort Class II (>=90%)			Comfort Class II (>=90%)		
		Fulfilled [hrs]	Fulfilled [%]	Unfulfilled [hrs]	Fulfilled [hrs]	Fulfilled [%]	Unfulfilled [hrs]
A2	2020	5.012	57,2	3.748	5.492	62,7	3.268
	2050	4.636	52,9	4.124	5.044	57,6	3.716
	2080	4.027	46,0	4.733	4.421	50,5	4.339
B1	2020	5.028	57,4	3.732	5.507	62,9	3.253
	2050	4.729	54,0	4.031	5.163	58,9	3.597
	2080	4.553	52,0	4.207	4.974	56,8	3.786

Although, for the moment, the optimised model might work better - and by looking at the B1 scenario, in 2080, the optimised building might have about the same range of temperatures of the status quo in 2020 - the results are once again clear: outdoor temperatures will rise in a way that will put informal dwellers to the test.

6.5. Retrofitting Abdullah's Building

This optimisation process is helpful to explore new solutions and get a new perspective on how dwellings might be built in the future. Nevertheless, we cannot forget that Cairo has a building stock of over 680.000 buildings, of which 87 per cent are residential. Looking at the Republic level, the median year of construction is 1978 (E. Raslan, Donarelli, & Angelis, 2018; R. Raslan & Mavrogianni, 2013).

Therefore, it comes without surprise that the next step in this research will touch upon the possibilities for retrofitting Abdullah's building. What strategies might improve thermal comfort in Abdullah's building by optimising the dwelling as it this today? By looking at the list of strategies used during the optimisation process, we can see the options that could be implemented for retrofitting. While it will not be possible to change the structure as described previously, three options might be used:

- Flat roof insulation
- Reflective flat roof [26]
- Implementation of double glazing

We can see in table 6.4 the results of the single implementation of the measures. IT-098-SQ is the status quo. Option A includes a layer of 10 centimetres EPS. While costing about 22.000 EGP is helpful to increase the number of comfortable hours by 5 per cent (total of 76 per cent). In option B, by applying a layer of 3 millimetres of ultra-white $BaSO_4$ film, and spending just

[26] The reflective roof was included at this point of the research only because the author found evidence of new research in this sense only a few days before printing this work. The study conducted by Li et al. shows that using a $BaSO_4$ nanoparticle film and a $BaSO_4$ nanoparticle acrylic paint assembled by the authors, it is possible to create a "super reflective paint" that has a solar reflectance above 97% and sky window emissivity of 0.95. Onsite field tests demonstrated that the temperature below the paint (and film) was maintained at 4,5-10°C below ambient temperature, while the commercial paint sample increased 6,8°C above ambient temperature. According to the researchers, S100 of this paint – although not available in the market yet – would be enough to be used on 150 m^2 (Li et al., 2020; Li, Peoples, Yao, & Ruan, 2021). For our research, we used the price of 30 EGP / m^2.

about 2.000 EGP, the thermal comfort increases by 3 per cent. By retrofitting the glazing and applying double glazing windows, the increase in comfort is 2 per cent, while the monetary costs would be 15.000 EGP. Incorporating all three measures would increase comfortable temperatures from 71 per cent (status quo) to 78 per cent. By looking a bit more into detail at the hourly frequency of the summer week, we can compare the models and see the influence of the measures on comfortable temperatures. The temperature variation between the different models is not significant on the ground floor.

Nevertheless, a lot is happening on the fourth floor (see figure 6.8). The temperatures range in which the status quo and the retrofitted model with double glazing (model C) look alike and during the warmer day (August 19th), reach 36,8°C. Model B (reflective paint) is cooler by 1,1°C (topping at 35,7°C). Model B (EPS) reaches 35,6°C, and model D, including all options, reaches a minimum of 35,2°C. According to these results, it seems reasonable to say that the most cost-effective strategy to follow is the reflection of solar gains from the roof. Thinking about the cost-effectiveness of the other two options, we can observe that, although more expensive, the insulation on the roof will surely bring more comfort than by changing the glazing.

Table 6.4 – Abdullah's retrofit results (for the complete table, see table A.13 the Appendix)

FREE FLOAT MODE YEARLY RESULTS TEMPERATURES	Abdullah's Building Retrofit				
	IT-098-SQ	A	B	C	D
Total Construction Cost (x1.000 EGP)	498	520	500	513	539
Embedded CO2 (t)	109	119	95	109	106
Comfortable Hours (Year; Max = 8760 hrs.)	6250	6657	6440	6354	6795
Comfortable Hours (Year; Max = 100%)	71%	76%	74%	73%	78%

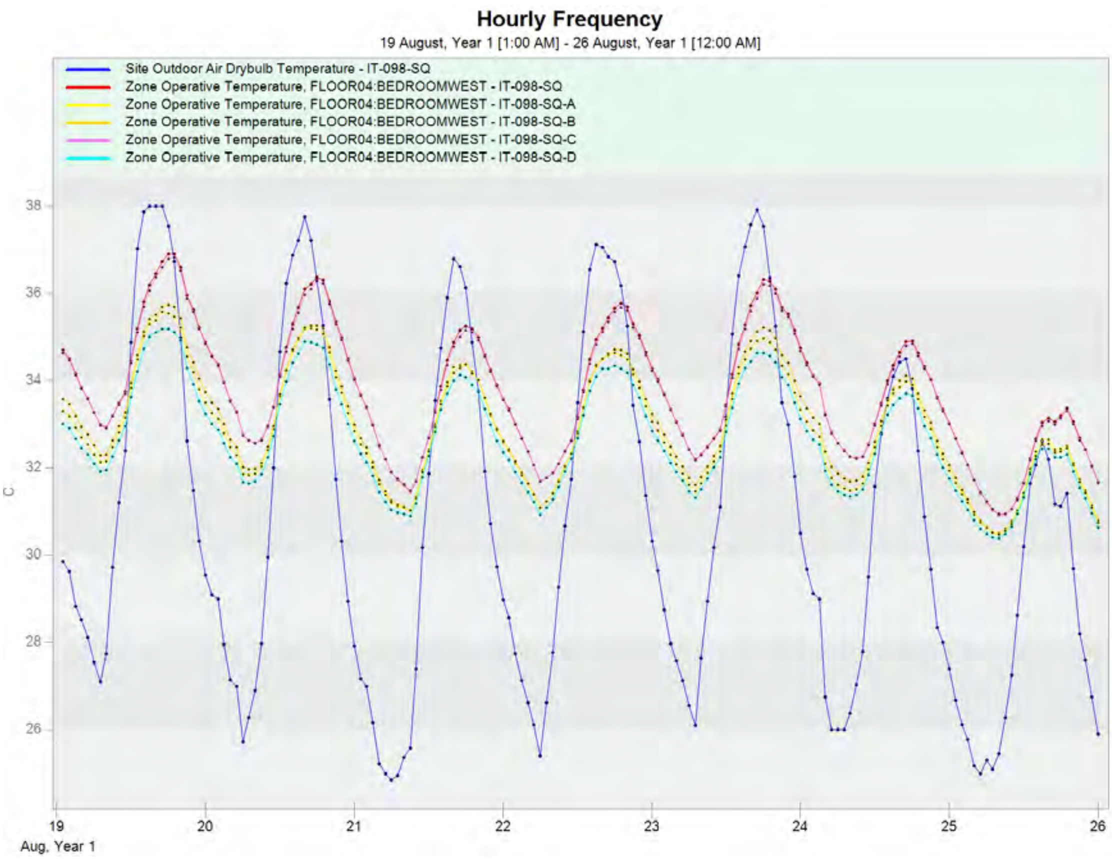

Figure 6.8 – Comparison of hourly frequency of the retrofitting options – Fourth floor (bedroom west).

6.6. Building Performance and Measures to Be Taken in Different Urban Settings

In this chapter, we have concentrated our efforts on a precise urban setting. While looking at what influences Abdullah's building most, we focused on minimising solar gains, conductive heat flow, and the interception and reflection of solar gains. We have realised with Abdullah's building sensitivity analysis (SA) that external factors such as orientation, adjacent buildings, and nearby buildings that protect Abdullah's building from sun radiation impact the building performance. But what would be the measures needed by Abdullah's building if the urban situation were different?

At this point, by conducting four SA studies, we expand the research to see to what extent the strategies and systems observed might impact the building in other urban settings[27]. Following SA, a parametric study (PA) based on the SA results is carried out. This will help understand, for each variable, the measures that have to be considered to obtain optimum comfort results.

The following scenarios are studied:

- A-status quo: Abdullah's building with adjacent buildings and opposite buildings,
- B-free front: Abdullah's building with adjacent buildings (without opposite buildings),
- C-free front and back: Abdullah's building with adjacent buildings (left and right),
- D-freestanding: Abdullah's building without buildings around.

For each analysis, the following variables are included: roof construction, external walls construction, windows, building orientation, window to wall ratio, window shading (louvres and overhangs), natural ventilation rate, infiltration rate. In figure 6.9, the four analyses are visualised, and in table 6.5, the variables are summarised in detail. For this analysis, we chose the month of August, and the status quo model was taken as a basis for carrying out the parametric analysis (PA).

6.6.1. Status Quo (A)

By observing the results of the A case – status quo – the standard regression coefficient is high (adjusted R^2 value = 0,9886; see table 6.6), meaning that most of the key sensitive input variables were identified. Thermal comfort is most strongly influenced by external wall construction. However, there is an inverse relationship. While we might expect that a low U-Value would increase thermal comfort, in this case, the opposite happens. The U-Value of the selected wall constructions that work best in this scenario has a U-Value between 1,1 and 1,2 W/m^2K (the tested range was 0,9-1,2 W/m^2K). It seems that in this case, the target for wall construction of $\leq 1{,}0$ W/m^2K, as specified by the Egyptian Green Building Code (see Hanna, 2015), would help in keeping the heat inside.

[27] While here we focus on the comfort inside the building, the following publications might give an insight into how buildings affect the block or the district thermal comfort:

Fahmy, Mahmoud, Elwy & Mahmoud. (2020). *A review and insights for eleven years of urban microclimate research towards a new Egyptian era of low carbon, comfortable and energy-efficient housing typologies.* // Alabsi, Song & Garfield. (2016). *Sustainable Adaptation Climate of Traditional Buildings Technologies in the Hot Dry Regions.* // Khalil, Ibrahim, Elgendy & Makhlouf. (2018). Could/should improving the urban climate in informal areas of fast-growing cities be an integral part of upgrading processes? Cairo case. // Fahmy & Sharples. (2009). *On the development of an urban passive thermal comfort system in Cairo, Egypt.*

Table 6.5 – Variables used for SA studies conducted in different urban scenarios

Strategy	Input	Variability	Options Description
Minimize conductive heat flow	Roof U-value	Target value = 0,50 W/m2K * Uncertainty is represented by binomial distribution Lower Bound = 0,4 W/m2K Upper Bound = 0,7 W/m2K	7 options: 0,40 / 0,45 / 0,50 / 0,55 / 0,60 / 0,65 / 0,70
	Wall U-value	Target value = 1,0 W/m2K * Uncertainty is represented by binomial distribution Lower Bound = 0,9 W/m2K Upper Bound = 1,20 W/m2K	7 options: 0,9 / 0,95 / 1,00 / 1,05 / 1,10 / 1,15 / 1,20
	Window U-Value	Target value = 1,90 W/m2K Uncertainty is represented by binomial distribution Lower Bound = 1,70 W/m2K Upper Bound = 2,30 W/m2K	7 options: 1,70 / 1,80 /1,90 / 2,00 / 2,10 / 2,20 / 2,30
	Internal Partition Construction	Target value = 1,60 W/m2K Uncertainty is represented by binomial distribution Lower Bound = 1,30 W/m2K Upper Bound = 2,10 W/m2K	9 options: 1,30 / 1,40 / 1,50 / 1,60 / 1,70 / 1,80 / 1,90 / 2,00 / 2,10
	Internal Floor Construction	Internal Floor Construction Uncertainty is represented by uniform distribution Lower Bound = 2,7 W/m2K Upper Bound = 3,5 W/m2K	3 options: 2,7 / 3,3 / 3,5
Minimize solar gains	Orientation	Overhang Uncertainty is represented by uniform distribution Lower Bound = 90° Upper Bound = 270°	5 options: 90° / 135° / 180° / 225° / 270°
	Window to Wall Ratio	Target value = 12% Uncertainty is represented by normal distribution Lower Bound = 10% * Upper Bound = 20% *	6 options: (mean=12 - Std. dev.=1,5
Interception of solar gains	Louvres	Window Louvres Uncertainty is represented by uniform distribution Lower Bound = ON Upper Bound = OFF	2 options: 0,5 m louvre (0,2 louvre, 0,3 distance from window) and OFF
	Overhang	Target value = 0,5 m Uncertainty is represented by binomial distribution Lower Bound = 0 m Upper Bound = 1,5	4 options: 0,0 m / 0,5 m / 1,0 m / 1,5 m
Promote ventilation	Air changes	Target value = 8 ac/h Uncertainty is represented by normal distribution Lower Bound = 4 ac/h Upper Bound = 14 ac/h	6 options: mean=8 - Std. dev.=2 lower side truncated=4
	Infiltration	Target value = 0,4 ac/h Uncertainty is represented by uniform distribution Lower Bound = 0,3 ac/h Upper Bound = 0,7 ac/h	5 options: 0,3 / 0,4 / 0,5 / 0,6 / 0,7

*Values as described by Hanna (2015) citing the Egyptian Green Building Code.

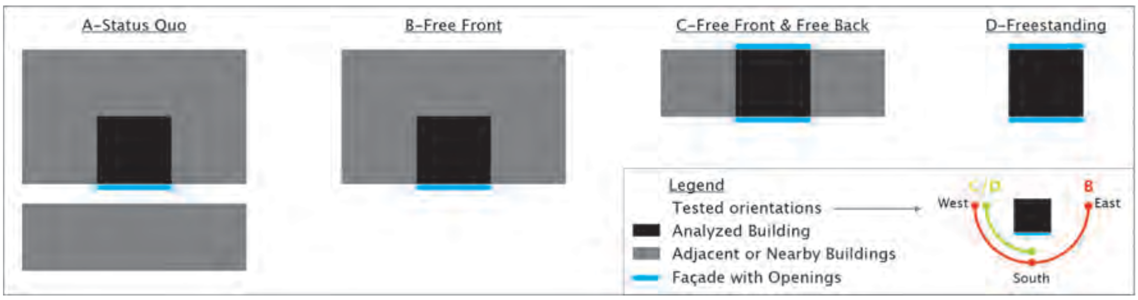

Figure 6.9 – Four urban scenarios and orientation settings – Analysis B is simulated with three orientation angles, Analysis C and D are simulated with two orientation angles.

Table 6.6 – Results of SA studies and variables influencing the results.

Scenario	Run	Type	Nr. Sims	Orientation	Results	Variables Included (last run)	Variables Exluded (last run)	Variable Influecing the Result
A	1	RND	200	ALL	**0,989**	Roof U-value / Wall U-value / Window U-Value / Orientation / Window to Wall / Louvres / Overhang / Air Changes / Infiltration	Thermal Mass / Internal Partition Construction	1. External wall construction 2. Flat roof construction 3. Overhang 4. Glazing type
B	4	LHS	100	S	**0.8823**	Roof U-value / Wall U-value / Window U-Value / Window to Wall / Louvres / Overhang / Infiltration / Thermal Mass	Orientation / Air Changes / Internal Partition Construction	1. External wall construction 2. Flat roof construction 3. Overhang 4. Infiltration (ac/h)
B	5	LHS	100	W	**0.9563**	Roof U-value / Wall U-value / Window U-Value / Window to Wall / Louvres / Overhang / Infiltration / Thermal Mass	Orientation / Air Changes / Internal Partition Construction	1. External wall construction 2. Flat roof construction 3. Overhang 4. Thermal mass
B	6	LHS	100	E	**0,9708**	Roof U-value / Wall U-value / Window U-Value / Window to Wall / Louvres / Overhang / Infiltration / Thermal Mass	Orientation / Air Changes / Internal Partition Construction	1. External wall construction 2. Flat roof construction 3. Overhang 4. Glazing type
C	9	LHS	140	S	**0.9544**	Roof U-value / Wall U-value / Window U-Value / Overhang. / Internal Floor construction	Orientation / Window to Wall / Louvres / Air Changes / Infiltration / Thermal Mass / Internal Partition Construction	1. External wall construction 2. Internal floor construction 3. Flat roof construction 4. Overhang
C	12	LHS	100	W	**0,8841**	Roof U-value / Wall U-value / Window U-Value / Window to Wall / Louvres / Overhang / Infiltration / Internal Partition Construction / Internal Floor construction	Orientation / Air Changes / Thermal Mass	1. Overhang 2. Internal floor construction 3. Flat roof construction 4. Glazing type
D	4	LHS	100	S	**0.9460**	Roof U-value / Wall U-value / Overhang / Infiltration	Window U-Value / Orientation / Window to Wall / Louvres / Air Changes / Thermal Mass / Internal Partition Construction	1. External wall construction 2. Flat roof construction 3. Overhang 4. Infiltration (ac/h)
D	5	LHS	100	W	**0.9713**	Roof U-value / Wall U-value / Overhang / Infiltration	Window U-Value / Orientation / Window to Wall / Louvres / Air Changes / Thermal Mass / Internal Partition Construction	1. Overhang 2. External wall construction 3. Flat roof construction 4. Infiltration (ac/h)

Legend: High Importance / Medium Importance / Low Importance

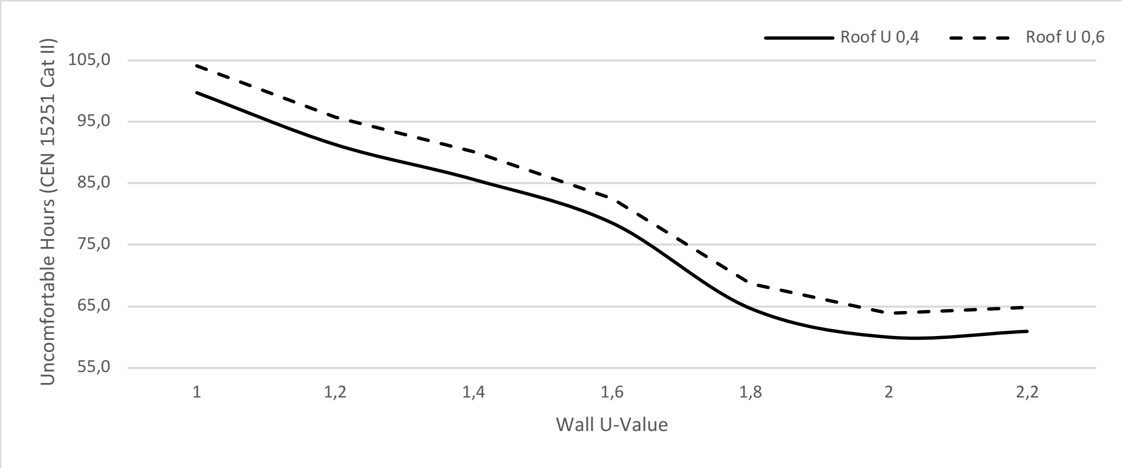

Figure 6.10 – Scenario A - South. Parametric analysis of wall and roof U-Value (uncomfortable hours).

Thermal comfort is also strongly influenced by flat roof construction, and in this case, the best ten per cent of the results have values between 0,4 – 0,55 W/m^{2}k. (This value is in accordance with the EGBC that requires ≤0,5 W/m^{2}K – see Hanna, 2015.) All other variables do not have a notable influence on comfort. Orientation is part of those variables: due to the dense urban context, the variation of comfort when changing the orientation of the building is not significant enough to influence operative temperatures. That can also be proved by running the same test excluding the variable orientation: no results are available after the trial. Why? Because after having simulated 100 iterations, the variance of the output – the range of the resulting comfortable hours – is so tiny that even if it is possible to simulate the different variant options between them, it is not possible to find the most relevant ones. By running a PA including the most influential parameters (wall and roof construction U-Values), it is possible to observe the following. When we look at figure 6.9, showing the number of uncomfortable hours in August, we can see that the two options taken for the roof (0,4 and 0,6 W/m^{2}K) are working as explained in the SA: the lower the U-Value, the higher the comfort. By focusing on the wall construction U-Values, and following the Roof 0,4 curve, we can observe that a U-Value of 1,0 lead to about 100 hours of uncomfortable hours. The curve reaches the lowest number of uncomfortable hours (about 60) at around 2,0 W/m^{2}K and then increases again. Therefore, while a U-Value of 2,0 W/m^{2}K is the maximum obtainable in this case, within this context, a U-value in the range of 2,0 and 2,2 W/m^{2}K is recommendable. The same PA carried out by fixing the wall U-value at 2,0 and 2,2 W/m^{2}K, but looking at different roof constructions (U-Values range between 0,2 – 2,0 W/m^{2}K) indicates that, while the difference in uncomfortable hours between the two wall constructions is minimal (1 hour), the range in which the roof construction shows more benefits is with a U-Value ≤1,0 (W/m^{2}K). Even increasing the roof construction to obtain a very good U-Value under 0,5, in this case, would be only partially beneficial (see figure A.11 in the Appendix).

6.6.2. Free Front (B)

The results of the SA carried out with the B scenario – with Abdullah's façade facing South - show a high standard regression coefficient (adjusted R^2 value = 0,8823), meaning that most of the key sensitive input variables were identified. In this case, comfort is most strongly influenced by wall construction (with an inverse relationship). Flat roof construction and overhang also

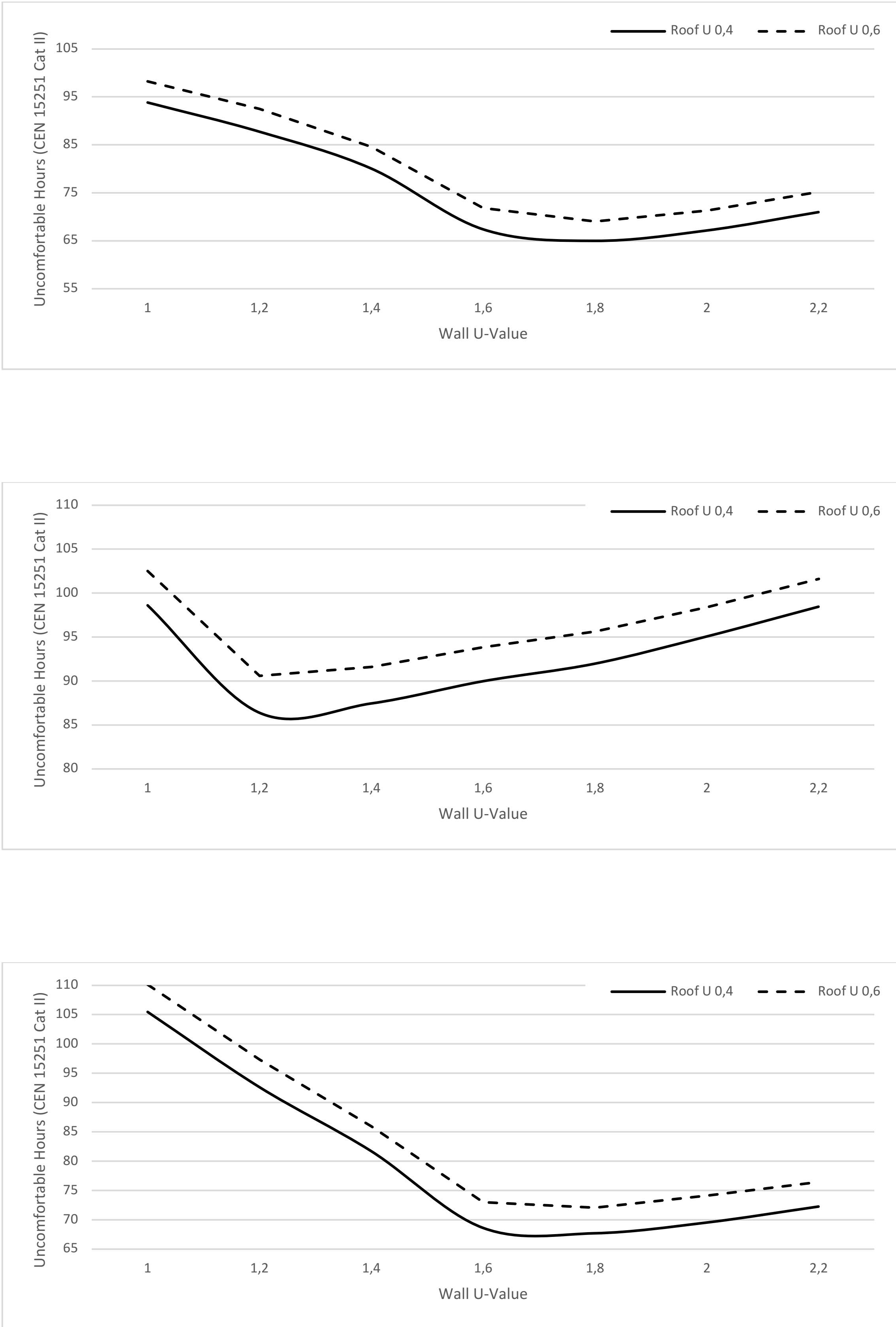

Figure 6.11 – Scenario B – South (Above), West (Center), East (Below). Parametric analysis of wall and roof U-Value (uncomfortable hours).

strongly influence comfort. All other tested variables do not have a notable influence on comfort.

As figure 6.11 shows, by running the PA for finding out the optimum wall construction, we can observe that the best results are obtainable when having a wall construction U-Value between 1,6 and 2,0 W/m^{2}K. The results of the PA by looking at the roof construction show a similar trend as in the previous model. The roof U-Value must be kept below 1,0 W/m^{2}K. By looking at the increased comfort brought using overhangs, we observe a good improvement with a 0,25 metres overhang, while having an overhang over 0,50 metres would not deliver any notable impact. Therefore, in this case, the suggested overhang length range should be between 0,25-0,5 metres (see figures A.12 and A.13 in the Appendix). The results of the SA carried out with the B scenario – with Abdullah's façade facing West – show similar results and a high standard regression coefficient (adjusted R^2 value West = 0,9563; adjusted R^2 value East = 0,9708), meaning that most of the critical sensitive input variables were identified. In both cases, comfort is most strongly influenced by wall construction and flat roof construction. An overhang also moderately affects comfort. All other tested variables do not have a notable influence on comfort. By looking at the PA results of the model facing West, having a wall construction with a U-Value higher than 1,2 and between 1,2 and 1,4 W/m^{2}K will have the highest impact on comfort. The PA done with building towards East show the best results with a wall U-Value higher than 1,6 and between 1,6 – 2,0 W/m^{2}K. Again, the PA conducted to see the effect of the roof demonstrate in both cases (East and West) that the U-Value should be lower than 1,0 W/m^2. As shown in figures A.16-A.19 (in the Appendix), the length of the overhang has an impact in energy used for lighting: therefore, it is suggested to keep it in the range between 0,5 – 1,0 meters.

6.6.3. Free Front and Back (C)

The results of the SA carried out with the C scenario – with Abdullah's façade facing South – show a high standard regression coefficient (adjusted R^2 value = 0,9544). Comfort is most strongly influenced by external wall construction (inverse relationship) and is also strongly affected by internal floor construction and flat roof construction. While comfort is also moderately influenced by an overhang, the glazing type does not have a notable influence. The results of the PA show that the external wall construction performs best in a range between 1,4 – 1,6 W/m^{2}K (see figure 6.12). A U-value lower than 1,2 would help in increasing operative temperatures. The U-Value line of the internal floor construction in figure 6.13 shows that values above 3,25 W/m^{2}K bring a decrease in comfort, values between 2,5 – 3,0 W/m^{2}K show the best results.

The SA carried out with the C scenario – with Abdullah's façade facing West – show a high standard regression coefficient (adjusted R^2 value = 0,884). Comfort is most strongly influenced by overhang length and is also moderately impacted by internal floor construction and flat roof construction. All other tested variables do not have a notable influence on comfort. As figure A.20 (in the Appendix) shows, the PA based on overhang length shows that the longer it is, the lowest the uncomfortable hours. With a 1,5 overhang, there might be an increase in thermal comfort of about 30 hours. Nevertheless, by taking visual comfort and lighting energy into consideration (figure 6.14), a length between 0,5 – 1,0 meters is recommended. An internal floor with a U-value between 2,75 – 3,25 W/m^{2}K delivers the best outcomes (see figure 6.13), and the flat roof behaves as observed in the other models.

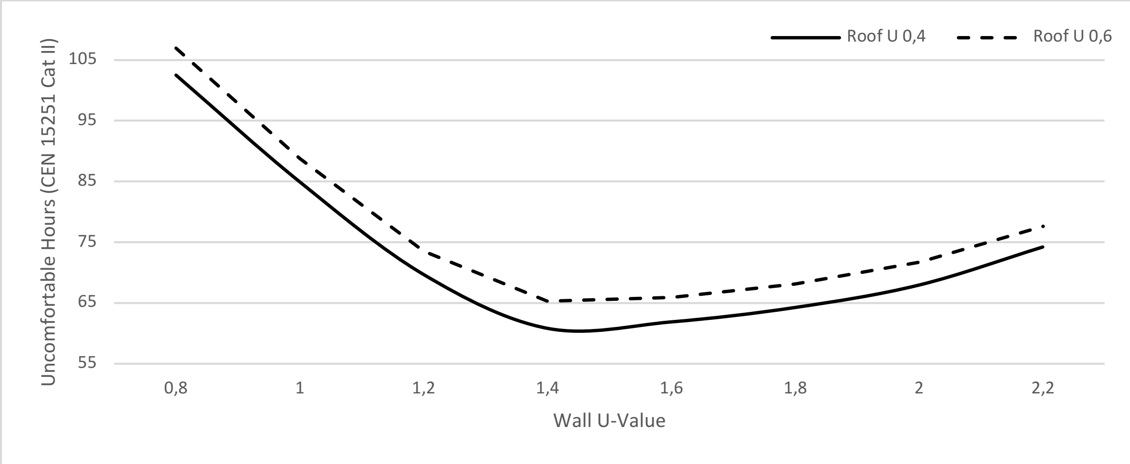

Figure 6.12 – Scenario C – South. Parametric analysis of wall and roof U-Value (uncomfortable hours).

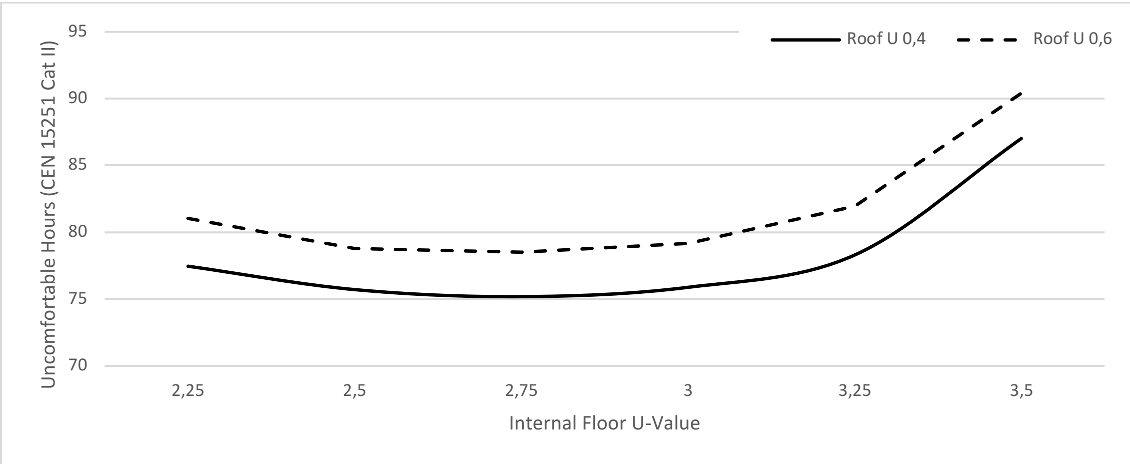

Figure 6.13 – Scenario C – South. Parametric analysis of internal floor and roof (uncomfortable hours).

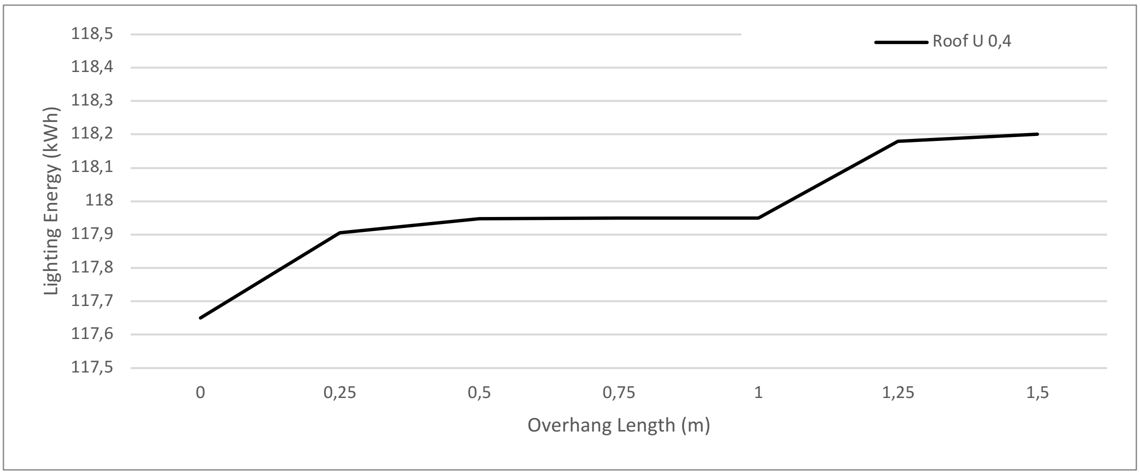

Figure 6.14 – Scenario C – West. Parametric analysis of overhang and roof (lighting energy).

6.6.4. Freestanding (D)

The results of the SA carried out with the D scenario – with Abdullah's façade facing South – show a high standard regression coefficient (adjusted R^2 value = 0,9460). Comfort is most strongly influenced by external wall construction (inverse relationship) and moderately affected by flat roof construction. The other tested variables do not have a notable influence on comfort. As shown in figure 6.15, the wall construction performs at its best between 0,8 – 1,0 W/m^{2}K. The roof behaves just like the previous PAs; the lower the U-Value, the better the comfort.

The results of the SA carried out with the D scenario – with Abdullah's façade facing West – show a high standard regression coefficient (adjusted R^2 value = 0,9713). Comfort is most strongly influenced by overhang length (inverse relationship) and moderately impacted by external wall construction and flat roof construction. Infiltration (ac/h) does not have a notable influence on comfort. As it happened before, when looking at the optimum for an overhang, a value between 0,5 – 1,0 meters is recommended (Figure A.23 in Appendix). Figure 6.16 shows that a wall construction U-Value between 0,4 – 0,6 W/m^{2}K obtains the best performance results. Values <0,4 should not be considered in this context.

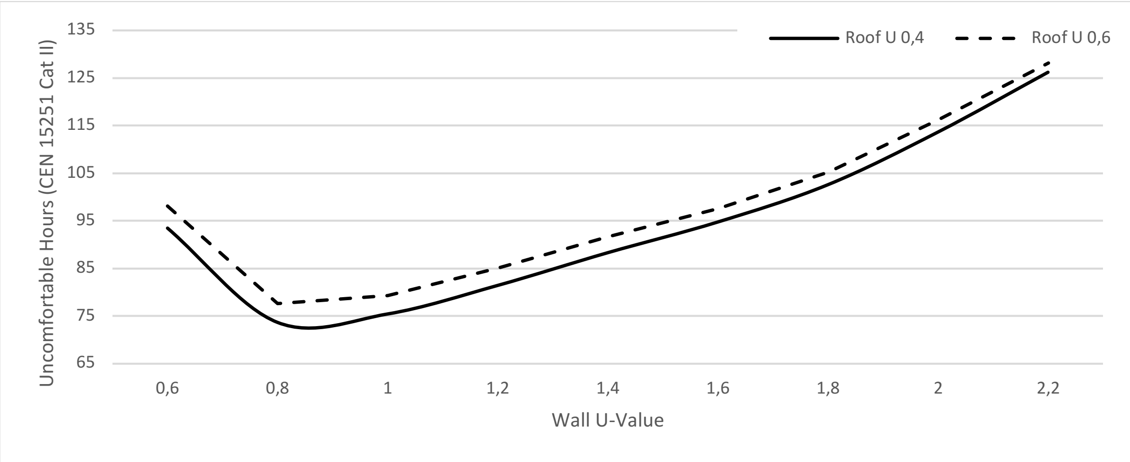

Figure 6.15 – Scenario C – West. Parametric analysis of wall and roof (uncomfortable hours).

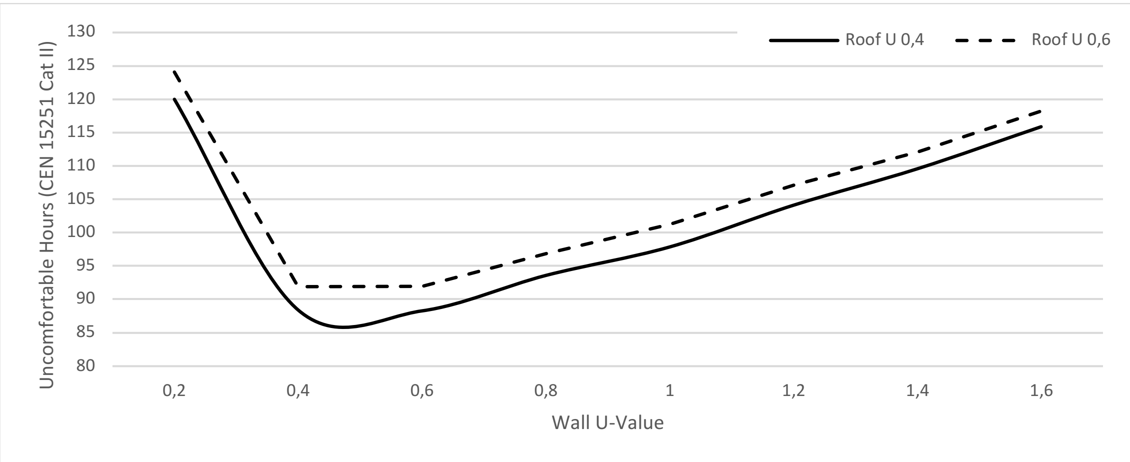

Figure 6.16 – Scenario D – West. Parametric analysis of wall and roof (uncomfortable hours).

Table 6.7 summarises all results discussed in this section. What we can observe here is manifold, and the effects that the surrounding buildings have is clearly shown. We can see that in almost every case, wall construction while being the factor influencing comfort temperature the most, should be in different ranges depending on the context and orientation. The more the building is embedded in the urban context, the less needs a low thermal transmittance wall construction. In general, the options facing East and West need a lower U-Value than those facing South. As shown on different tables, by decreasing U-Values over the given ranges, discomfort hours rise. This is most probably due to the heat mass that does not have enough time to release heat and be recharged with cooler air temperature during the night.

The best range for the roof's U-Value is constant in all cases (<1,0 W/m^{2}K). Overhangs perform best in a range between 0,25 – 0,5 metres when the windows face South, while they should be between 0,5 – 1,0 metres when facing East and West. By doing so, we found the optimum between intercepting solar gains and electricity demand for lighting. Scenario 03 is the only one showing a significant influence of internal floor constructions. If a building faces South, the U-Value might range between 2,5 – 3,0 (W/m^{2}K). When facing West – most probably because on the Southern side, a nearby building cuts solar radiation gains and minimises conductive heat – it might be a bit higher.

Table 6.7 – Results of PA studies (best range) for most influencing parameters on different scenarios.

Scenario A - Status Quo				INPUT			OUTPUT
Nr.	**Orient.**	**(SA)**	**Par. 01**	**Range 01**	**Par. 02**	**Range 02**	**Best Range**
1	South	0,989	**Walls U**	0,90 - 1,40 (W/m2K)	Roof U	0,40 / 0,60	**-**
2	South	0,989	**Walls U**	1,00 - 2,20 (W/m2k)	Roof U	0,40 / 0,60	**2,0 - 2,2**
3	South	0,989	**Roof U**	0,20 - 2,00 (W/m2k)	Walls U	2,0 / 2,2	**<1,0**

Scenario B - Free Front				INPUT			OUTPUT
Nr.	**Orient.**	**(SA)**	**Par. 01**	**Range 01**	**Par. 02**	**Range 02**	**Best Range**
1	South	0,8823	**Walls U**	1,00 - 2,20 (W/m2k)	Roof U	0,40 / 0,60	**1,6 - 2,0**
2	South	0,8823	**Overhang**	0,00 - 1,50 (m)	Roof U	0,40 / 0,60	**0,25 - 0,5**
3	South	0,8823	**Roof U**	0,20 - 2,00 (W/m2K)	Walls U	1,6 / 1,8	**<1,0**
1	West	0,9563	**Walls U**	0,60 - 2,20(W/m2K)	Roof U	0,40 / 0,60	**1,2 - 1,4**
2	West	0,9563	**Roof U**	0,20 - 2,00 (W/m2K)	Walls U	1,6 / 1,8	**<1,0**
3	West	0,9563	**Overhang**	0,00 - 1,50 (m)	Roof U	0,40 / 0,60	**0,5 - 1,0**
1	East	0,9708	**Walls U**	0,60 - 2,20 (W/m2K)	Roof U	0,40 / 0,60	**1,2 - 1,4**
2	East	0,9708	**Roof U**	0,20 - 2,00 (W/m2K)	Walls U	1,6 / 1,8	**<1,0**
3	East	0,9708	**Overhang**	0,00 - 1,50 (m)	Roof U	0,40 / 0,60	**0,5 - 1,0**

Scenario C - Free Front & Back				INPUT			OUTPUT
Nr.	**Orient.**	**(SA)**	**Par. 01**	**Range 01**	**Par. 02**	**Range 02**	**Best Range**
1	South	0,9544	**Walls U**	0,60 - 2,20 (W/m2K)	Roof U	0,40 / 0,60	**1,4 - 1,6**
2	South	0,9544	**Int Floors**	2,25 - 3,50 (W/m2K)	Roof U	0,40 / 0,60	**2,5 - 3,0**
3	South	0,9544	**Roof U**	0,20 - 2,00 (W/m2K)	Walls U	1,6 / 1,8	**<1,0**
1	West	0,8841	**Overhang**	0,00 - 1,50 (m)	Roof U	0,40 / 0,60	**0,5 - 1,0**
2	West	0,8841	**Int Floors**	2,25 - 3,50 (W/m2K)	Roof U	0,40 / 0,60	**2,75 - 3,25**
3	West	0,8841	**Roof U**	0,20 - 2,00 (W/m2K)	Walls U	1,6 / 1,8	**<1,0**

Scenario D - Freestanding				INPUT			OUTPUT
Nr.	**Orient.**	**(SA)**	**Par. 01**	**Range 01**	**Par. 02**	**Range 02**	**Best Range**
1	South	0,946	**Walls U**	0,20 - 1,60 (W/m2K)	Roof U	0,40 / 0,60	**0,8 - 1,00**
2	South	0,946	**Roof U**	0,20 - 2,00 (W/m2K)	Walls U	0,8 - 1,00	**<1,0**
1	West	0,9713	**Overhang**	0,00 - 1,50 (m)	Roof U	0,40 / 0,60	**0,5 - 1,0**
2	West	0,9713	**Walls U**	0,20 - 1,60 (W/m2K)	Roof U	0,40 / 0,60	**0,4 - 0,6**

6.7. Chapter Conclusions, Limitations and Outlook

This chapter started by answering the question *which strategies and systems used in the past might be transferred to an informal building to optimise thermal and energy performance?* We realised that minimising solar gains, minimising conductive heat flow, intercepting, and reflecting solar gains, might be the strategies to enhance the building's thermal performance. Due to the limited space at disposal, the promotion of ventilation might work only partially.

The optimisation study of the informal building was done with the help of Sensitivity Analysis and a multi-objective study in which more than 300 iterations were simulated according to different variables and options. Five iterations, including the status quo, were studied further. Starting with a thermal performance value of 71 per cent of comfortable hours in the status quo, we found that comfort can be increased to 88 per cent, but that implies having higher construction costs (+19,6 per cent) and environmental costs (+8,2 per cent). The biggest win of this solution is probably the decreasing operative temperatures on the upper floors: peak temperatures in August can be reduced by almost 2° C. This exploration opened to new opportunities.

Digging further into the optimisation process, a new optimum model was created. It was found that by minimising the use of concrete and clay and increasing the use of soil bricks, it would be possible to move from the skeleton structure to a wall bearing system. By doing so, it is possible to obtain better comfort results (91 per cent of hours in the comfort zone), a reduction of embedded CO_2 of 50 per cent with an increase in construction costs by 4,4 per cent. Thinking about the long-term effects of implementing such strategies, the comparison between the status quo and optimum models cleared all doubts about the comfort performance of buildings within different climate scenarios. To have responsive buildings made to withstand temperature rises require a change of mind, and action needs to be taken now.

The retrofit study showed that the reflection of solar radiations might be very effective in reducing operative temperatures while also being cost-effective. Thinking again on the long term and the effects during the different seasons, undoubtedly the use of insulation on the roof is the best option while being also the most expensive. Changing glazing does not seem to bring many benefits in this context.

The study carried out with the help of Sensitivity and Parametric Analyses of an informal building in different urban situations gave more than one hint about the parameters that influence thermal comfort the most. Furthermore, they endowed us with the possibility of understanding in which range the parameters might affect positively operative temperatures. Having a roof construction U-Value under 1,0 W/m^2K is necessary for any situation. The wall construction thermal transmittance is the most influential parameter in all denser urban settings, regardless of the orientation. In less dense scenarios, the same can be said when the main façade faces South. Keeping the U-Values within the ranges discussed positively impacts operative temperatures. Over optimising thermal transmittance has a negative influence on comfort. Another passive system that plays a crucial role in comfort temperatures is the overhang. While towards South shorter overhangs might be used, towards West and East, they should be long enough to cut sun radiations, without exceeding a length that might increase electricity demand for lighting. We have also found that internal floor constructions play a significant role in operative temperatures, at least in the scenario in which the building has a free front and a free back. Depending on the building orientation, the thermal transmittance needs to be in the proper range.

For directing us towards the new vernacular, this chapter has touched upon different topics, bringing new insights into informal buildings that shortly might become more climate-responsive and comfortable as of today. We have taken inspiration from strategies used in the past. We have been able to optimise digital models by looking at the impact a building might have on monetary and environmental costs. Nevertheless, there have been some study limitations and challenges that need to be addressed. This, with the hope that both the author and other researchers might study further such typologies of buildings and start testing and transferring this knowledge into practice.

While being an incredible tool for rapid prototyping, building performance simulation software requires a lot of time to set up models and run complex simulations (as in the optimisation process). The second point is one of the reasons for limiting most of the simulations work done in this chapter to a restricted number of days or weeks. We have typically chosen August to observe the building performance because it is the month with the most uncomfortable hours. On the other hand, optimisation studies done by looking at the whole year will permit to find best-fit solutions that might be useful also for giving recommendations useful in different periods of the year. To do so, a modeller might need either infinite time at disposal (which is quite unrealistic) or adequate technical infrastructure (which might be realistic in the proper research environment).

As we have seen at the beginning of the chapter, this study focuses on optimisation options that do not require any change of the building geometry. Further studies experimenting with different geometries might look at how ventilation might be optimised to increase thermal comfort by changing the building's plan. Furthermore, the dynamic characteristics of materials should be analysed further. After the optimisation process, and therefore almost at the end of the research, the author realised that the specifications of "air" (as material) given in DesignBuilder is not consistent with the one specified in the EN ISO 10456. Therefore, when looking at the thermal mass calculations following the EN ISO 13786 norm, inconsistencies were found in the resulting U-values, time shifts, and heat capacity. Hence, for this part of the study, the focus was kept on thermal transmittance, which, in any case, seemed to bring us towards good results.

While looking at design strategies and passive systems is the first step to increasing comfort and lowering building energy consumption, further research into the remaining sub-systems connected with the building is needed in this context. Knowing more about user behaviour, equipment, active systems (such as fans and HVAC), and the effects of measures beyond the building scale might give a further understanding to tackle issues related to operative temperatures and energy consumption.

Further studies and analyses focusing on climate projections and the building lifecycle will help decrease resistance to innovation in the building sector, which, as we realised, stagnates thanks to the lobbying work done by local and international construction companies. Furthermore, by considering monetary and environmental costs, the effects that a climate-responsive building can bring become clear: both for the end-users wallet (which in an informal environment is pretty tide) and on an environmental level (which does look quite bad).

7. Closing Remarks

This research summarises a series of studies done to answer the question *to what extent is it possible, by learning from vernacular strategies, to optimise the contemporary architecture in dry and hot climates to meet the end user's thermal comfort expectations while being environmentally sound?*

Before delving into Cairo, the comparison of tools to partially help answer this question was carried out. Then, we looked into the Egyptian and Cairenes climates. While looking at general strategies to be adopted in buildings, mainly to keep out summer heat gains, we had an introduction to climate projections and the effects that increasing temperatures might have on two typologies of buildings.

In chapters four and five, while comparing dwellings built at different times, we first understood what can be learned from vernacular architecture. We realised that quite differently to what happened in ancient times or just before the fifties, the pressure on land prices, on affordable housing, and the lack of regulations in the past decades have created a parallel and very triumphant reality, in which housebuilders' priorities are evident: economic use of space, economical use of resources and cheap workforce – especially in the cases where families built most by themselves. Most of the traditional architectural vocabulary has therefore gotten lost. Nevertheless, the rapid growth, organic and somehow efficient development of highly dense neighbourhoods seems to be the best fit, considering the socio-economic conditions of most of its inhabitants. So, suppose we define *extents* by economic possibilities and what the market has to offer); in that case, the *extent* of optimising a building and having a benefit on thermal comfort seems to be limited to what we can see today and to what was described as *contemporary vernacular*.

In chapter six, we realised pretty early that most of the design strategies and passive systems used in the past for increasing ventilation are not implementable in Cairene's informal context. This is again due to the value that each built square meter has. While the habits of city dwellers have changed through time and have been adapting to a dense environment, more importance is given today to the internal living space of the habitation. In any case, we have found that some strategies and systems might be implemented in this context for improving operative temperatures, decreasing energy consumption, and meeting end-users' expectations. Some well-performing options include the implementation of relatively expensive material. Some others require the use of materials that have been neglected (soil bricks) or still have to be commercialised (super-white paint); yet have the qualities to improve comfort. We found that getting back to the strategical use of a wall bearing structure, besides helping increase the well-being of its inhabitants, would also have a more negligible impact on GHG emissions, and therefore a smaller carbon footprint.

If informal homebuilders would be ready to invest in the present, in the future, and embrace a *new vernacular* building philosophy, that within this context, can be adaptable and responsive to a changing climate, the *extent* and range for improving this building typology increase considerably. The effects of such measures, if taken, could go beyond local users' needs and could make an active impact within the adaptation and mitigation strategies that need to be taken today to tackle climate change.

So, the last question that should be answered here is *how do we get there?*

Well, in a perfect and just world, the first step would be to draw a strategical roadmap that, including all stakeholders, would facilitate the transition process to implement the abovementioned measures in a short amount of time. The good news is that such roadmaps exist. The 2030 Agenda for Sustainable Development is one of them, and SDGs such as good health and living (03), affordable and clean energy (07), industry innovation and infrastructure (09), reduced inequalities (10), sustainable cities and communities (11), responsible consumption and production (12), climate action (13), peace, justice and strong institutions (16), and partnership for the goals (17) are all linked in one way or the other with the topic of this research. The Government of Egypt is committed to achieving the SDGs and, according to its latest 2021 Voluntary National Review, besides other accomplishments, right now the Government of Egypt is evaluating "values and the targets of SDGs indicators in all governorates in order to target local developmental gaps" (Permanent Mission of the Arab Republic of Egypt to the United Nations, 2021). Added to that, Egypt is also one of the signatories of the Paris Agreement. Besides other essential points, the Republic of Egypt, with its signature "recognises the parity between mitigation and adaptation and mandates a balanced means of implementation for both", "admits the right of future generations for a better and safer livelihood while considering the special needs and circumstances of the developing countries", and "respects the African countries request of pursuing efforts to raise the ambition to limit temperature increase to below 1.5 C in order to reduce the adaptation burden on our countries" (Arab Republic of Egypt, 2016).

On the other hand, while a roadmap and commitment are there, we do not live in a perfect world. Over the past decades, Egypt has been able to improve its human development by increasing life expectancy, expanding access to education, reducing the burden of chronic diseases, and more. Nevertheless, as it might happen to rapidly growing countries, the Republic also faces many challenges that go from the alleviation of poverty to meeting the domestic energy demand; and from ensuring access to water to secure domestic food production (Bohl, Hanna, Scott, Moyer, & Hedden, 2018). With such issues being the prime concern of the African State, climate change issues are still not a priority (Dabaieh et al., 2021). In the third chapter, we have dealt with the consequences of climate change and rising temperatures, and in chapters five and six, we have explored what the living conditions in informal buildings might look like in the future. Other authors have already explored the consequences of this, especially for the most vulnerable groups in urban informalities (Khalil, Ibrahim, Elgendy, & Makhlouf, 2018).

So, if the government alone cannot focus on climate change, solutions need to be found elsewhere. In recent years, Egypt has experienced the growth of grassroots initiatives, activists' movement, and NGOs' efforts in different fields. If these efforts would be coped with the governmental work, it might be possible to tackle climate change threats holistically while sharing the valuable experiences coming from community members. As Academia might play a crucial role in filling the gap between top-down and bottom-up strategies, a lot of effort should be put into the right ways of communicating climate change issues. (Dabaieh et al., 2021). Within its limitations and hoping that it will be disseminated, this research aims to be part of this movement. While there is always space for improvement, the times we live require a fast pace for finding innovative and implementable solutions. The methodology and tools used for this study have proven to be valid instruments for rapid prototyping. Moreover, they could be integrated into any setting: being informal, formal, in hot climates or elsewhere.

We live in strange times.

On the one hand, we are part of those human beings that were born in the Anthropocene. Never in the history of the world have human beings been able to age so long, build such a wealth system, be globally-connected, and experience such rapid technological and urban development. Within one century, the average life expectancy increased from about 40 years to more than 70 years (Max Roser & Ritchie, 2013). Within one generation, humanity has practically eradicated deadly diseases such as polio and found effective treatments for HIV/AIDS. During the same time, we have been able to build cities in the desert and send tourists into space.

On the other hand, climate change, which is also the result of the effects of what we have created in the last couple of hundred years, is the biggest threat to be tackled globally. Harari wrote in 2018 that "climate change might be far beyond the concerns of people in the midst of a life-and-death emergency, but it might eventually make the Mumbai slums unhabitable, send enormous new waves of refugees across the Mediterranean, and lead to a worldwide crisis in health care" (Harari, 2018). This gives only a tiny idea of different threats at different scales that we may challenge if we do not take responsibility and action now.

Although unrelated to climate change, right now, we are already experiencing a worldwide healthcare crisis. Due to COVID-19, besides the losses of human life, we have experienced the instability that can be brought on a global scale and that can touch any of us. Furthermore, and this is a positive note, we are also experiencing what it means to be committed to tackling a global threat. Things are not perfect yet. Nevertheless, we are enduring in making sure that regulations are enacted and implemented, that technologies (such as testing and vaccines) are developed further and brought to the public. And (most of) the governments keep a transparent dialogue with citizens, industry, and all other stakeholders, to minimise human losses and get back to normal. The author is aware that in the process of combatting the pandemic, mistakes have been made. In any case, would not the lesson learned with COVID-19 be an excellent example to start tackling climate change?

And finally, what is our role as researchers of the built environment? Not only we do have the moral duty to study concepts and find strategies that enable the implementation of adaptation and mitigation measures. We also need to find innovative ways to disseminate this knowledge and make sure that stakeholders involved in the various processes of human production and systems of governance can make use of it, letting both society and the environment benefit from it.

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Visual Impressions

Figure VIS.1 – Informal (lower part) and formal Cairo from above. (Photo G. Vignola)

Figure VIS.2 – In an informal street. (Photo G. Vignola)

Figure VIS.3 – Informal housing – Passive systems for intercepting solar gains. (Photo G. Vignola)

Figure VIS.4 – Traditional building – Passive systems for intercepting solar gains and *mashrabiya*. (Photo G. Vignola)

Figure VIS.5 – Traditional building – Lantern (*shukhshakhah*). (Photo G. Vignola)

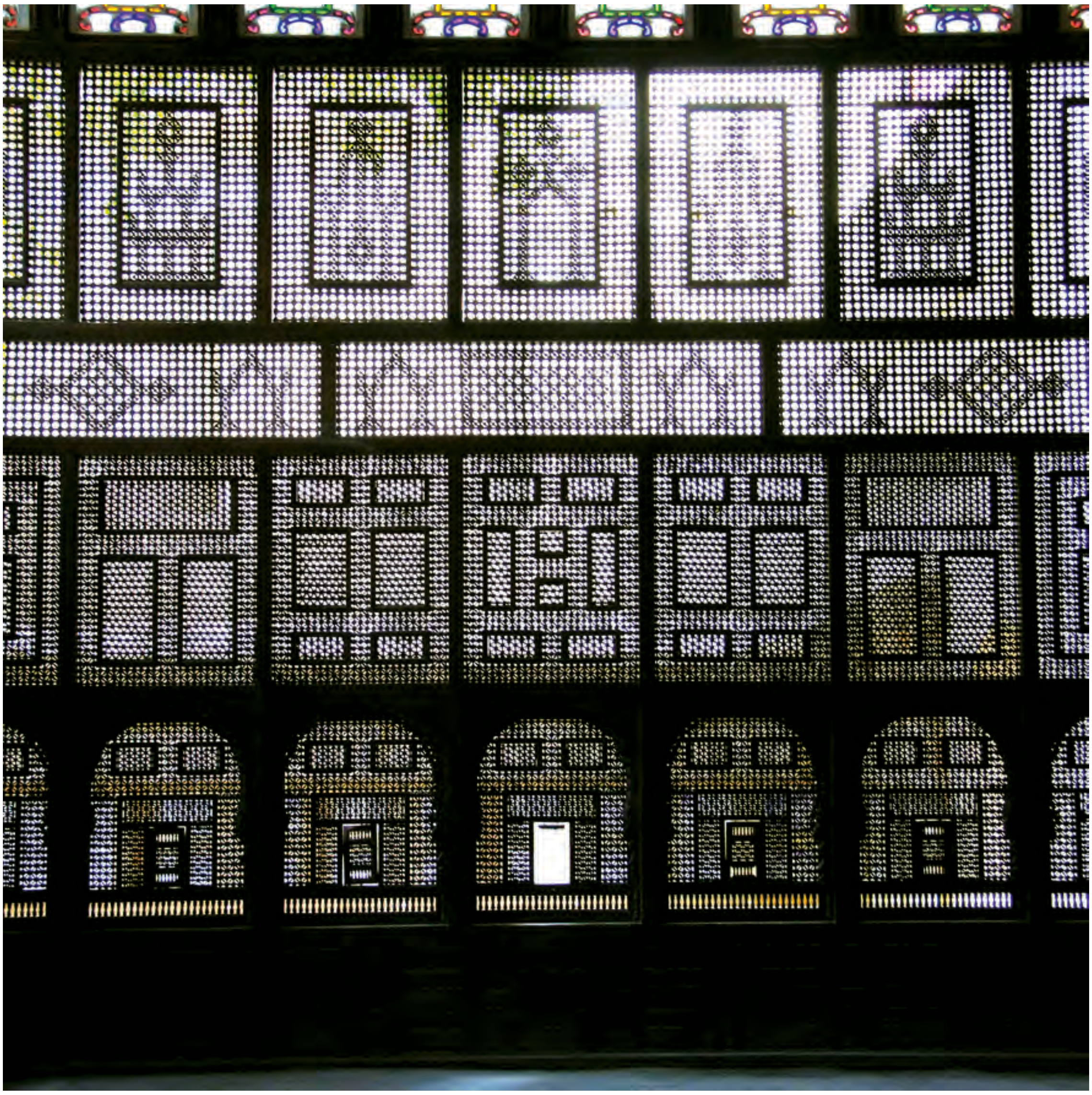

Figure VIS.6 – Traditional building – Latticework. (Photo G. Vignola)

Figure VIS.7 – Informal housing on agricultural land on the way to 6th of October. (Photo G. Vignola)

Figure VIS.8 – Informal housing – Passive and active cooling systems. (Photo G. Vignola)

Figure VIS.9 – At the Cairo University. (Photo G. Vignola)

Figure VIS.10 – Inspiration. (Photo G. Vignola)

Appendix Chapter 02

Table A.1 – Material specifications lightweight case (ASHRAE, 2017, p. 22).

Element	k, W/(m·K)	Thickness, m	U, W/(m2·K)	R, (m2·K)/W	Density, kg/m3	cp, J/(kg·K)
Lightweight Case: Exterior Wall (inside to outdoors)						
Interior surface coefficient			8,290	0,121		
Plasterboard	0,160	0,012	13,333	0,075	950,000	840,000
Fiberglass quilt	0,040	0,066	0,606	1,650	12,000	840,000
Wood siding	0,140	0,009	15,556	0,064	530,000	900,000
Exterior surface coefficient			29,300	0,034		
Total air-air			**0,514**	**1,944**		
Total surf-surf			**0,559**	**1,789**		
Lightweight Case: Floor (inside to outdoors)						
Interior surface coefficient			8,290	0,121		
Timber flooring	0,140	0,025	5,600	0,179	650,000	1200,000
Insulation	0,040	1,003	0,040	25,075	0 b	0 b
Total air-surf			**0,039**	**25,374**		
Total surf-surf			**0,040**	**25,254**		
Lightweight Case: Roof (inside to outdoors)						
Interior surface coefficient			8,290	0,121		
Plasterboard	0,160	0,010	16,000	0,063	950,000	840,000
Fiberglass quilt	0,040	0,112	0,358	2,794	12,000	840,000
Roofdeck	0,140	0,019	7,368	0,136	530,000	900,000
Exterior surface coefficient			29,300	0,034		
Total air-air			**0,318**	**3,147**		
Total surf-surf			**0,334**	**2,992**		
Summary: Lightweight Case						
Component	**Area, m2**	**UA, W/K**				
Wall	63,600	32,715				
Floor	48,000	1,892				
Roof	48,000	15,253				
South window	12,000	36,000				
Infiltration		18,440 c				
Total UA (with south glass)		**104,300**				
Total UA (without south glass)		**68,300**				
		ach	**Volume, m3**	**Altitude, m**		
		0,500	129,600	1609,000		

a. Informative Note: The interior film coefficient for floors and ceilings is a compromise between upward and downward heat flow for summer and winter.
b. Underfloor insulation has the minimum density and specific heat the program being tested will allow, but not <0.
c. Informative Note: UA corresponding to infiltration based on ach x volume x (specific heat of air) x (density of air at specified altitude).

Table A.2 – Material specifications lightweight case - Inputs and results in Primero.

Element	k, W/(m·K)	Thickness, m	U, W/(m2·K)	R, (m2·K)/W	Density, kg/m3	cp, J/(kg·K)
Lightweight Case: Exterior Wall (inside to outdoors) - Light_ExteriorWall						
Interior surface coefficient			7,692	0,130		
Plasterboard	0,160	0,012	13,333	0,075	950,000	840,000
Fiberglass quilt	0,040	0,066	0,606	1,650	12,000	840,000
Wood siding	0,140	0,009	15,556	0,064	530,000	900,000
Exterior surface coefficient			25,000	0,040		
Total air-air			0,510	**1,959**		
Total surf-surf			0,559	**1,789**		
Lightweight Case: Floor (inside to outdoors) - Light_Floor						
Interior surface coefficient			5,882	0,170		
Timber flooring	0,140	0,025	5,600	0,179	650,000	1200,000
Insulation	0,040	1,003	0,040	25,075	1,000	1,000
Total air-surf			0,039	**25,424**		
Total surf-surf			0,040	**25,254**		
Lightweight Case: Roof (inside to outdoors) - Light_Roof						
Interior surface coefficient			10,000	0,100		
Plasterboard	0,160	0,010	16,000	0,063	950,000	840,000
Fiberglass quilt	0,040	0,112	0,358	2,795	12,000	840,000
Roofdeck	0,140	0,019	7,368	0,136	530,000	900,000
Exterior surface coefficient			25,000	0,040		
Total air-air			0,319	**3,133**		
Total surf-surf			0,334	**2,993**		
Summary: Lightweight Case						
Component	**Area, m2**	**UA, W/K**				
Wall	63,600	32,461				
Floor	48,000	1,888				
Roof	48,000	15,320				
South window	12,000	34,800		to be checked		
Infiltration		18,440	c	to be checked		
Total UA (with south glass)		**102,909**				
Total UA (without south glass)		**68,109**				
		ach	**Volume, m3**	**Altitude, m**		
		0,500	129,600	1609,000		

a. Informative Note: The interior film coefficient for floors and ceilings is a compromise between upward and downward heat flow for summer and winter.
b. Underfloor insulation has the minimum density and specific heat the program being tested will allow. Primero allows 1, no 0
c. Informative Note: UA corresponding to infiltration based on ach x volume x (specific heat of air) x (density of air at specified altitude).

Table A.3 – Material specifications heavyweight case (ASHRAE, 2017, p. 28).

Element	k, W/(m·K)	Thickness, m	U, W/(m2·K)	R, (m2·K)/W	Density, kg/m3	cp, J/(kg·K)
Heavyweight Case: Exterior Wall (inside to outside)						
Interior surface coefficient			8,290	0.121		
Concrete block	0,510	0,100	5,100	0.196	1400,000	1000,000
Foam insulation	0,040	0,0615	0.651	1,537	10,000	1400,000
Wood siding	0,140	0,009	15,556	0,064	530,000	900,000
Exterior surface coefficient			29,300	0,034		
Total air-air			**0,512**	**1,952**		
Total surf-surf			**0,556**	**1,797**		
Heavyweight Case: Floor (inside to outside)						
Interior surface coefficient a			8,290	0,121		
Concrete slab	1,130	0,080	14,125	0,071	1400,000	1000,000
Insulation	0,040	1,007	0,040	25,175	0 b	0 b
Total air-surf			**0,039**	**25,366**		
Total surf-surf			**0,040**	**25,246**		
Heavyweight Case: Roof (inside to outside) c						
Interior surface coefficient a			8,290	0,121		
Plasterboard	0,160	0,010	16,000	0,063	950,000	840,000
Fiberglass quilt	0,040	0,1118	0,358	2,794	12,000	840,000
Roofdeck	0,140	0,019	7,368	0,136	530,000	900,000
Exterior surface coefficient			29,300	0,034		
Total air-air			**0,318**	**3,147**		
Total surf-surf			**0,334**	**2,992**		
Summary: Lightweight Case						
Component	**Area, m2**	**UA, W/K**				
Wall	63,600	32,580				
Floor	48,000	1,892				
Roof	48,000	15,253				
South window	12,000	36,000				
Infiltration		18,440	d			
Total UA (with south glass)		104,165				
Total UA (without south glass)		68,165				
		ach	**Volume, m3**	**Altitude, m**		
		0,5	130	1.609,000		

a. Informative Note: The interior film coefficient for floors and ceilings is a compromise between upward and downward heat flow for summer and winter.
b. Underfloor insulation has the minimum density and specific heat the program being tested will allow, but not <0.
c. Informative Note: UA corresponding to infiltration based on ach x volume x (specific heat of air) x (density of air at specified altitude).
d. Informative Note: UA corresponding to infiltration based on ach × volume × (specific heat of air) × (density of air at specified altitude).

The followings are the strings modified in the *Zeitprofil Personen.lib* file (in the original file, values are followed by tabs and not semicolons):

```
*diese Datei enthält das Nutzungsprofil die Personenbelegung

*zu jeder Nutzung gehören 3 Profile: a) Mo bis Fr, b) Sa und c) So

*Nr.; Wo-tage; np01; np02; np03; np04;  np05; np06; np07; np08; np09; np10; np11;
np12; np13; np14; np15; np16; np17; np18; np19; np20.0; np21; np22; np23; np24
1; a; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1;
1; b; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1;
1; c; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1;
```

The followings are the strings modified in the *Zeitprofil Arbeithilfen.lib* file (in the original file, values are followed by tabs and not semicolons):

```
*diese Datei enthält das Nutzungsprofil die Personenbelegung

*zu jeder Nutzung gehören 3 Profile: a) Mo bis Fr, b) Sa und c) So

*Nr.; Wo-tage; np01; np02; np03; np04;  np05; np06; np07; np08; np09; np10; np11;
np12; np13; np14; np15; np16; np17; np18; np19; np20.0; np21; np22; np23; np24
1; a; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0;
1; b; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0;
1; c; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0;
```

The followings are the strings modified in the *Waermelasten Nutzung.lib* file:

```
* diese Datei enthält die Wärmelasten in W/m², und zwar 10 Zahlen für

*Nr.  Personenbelegung  tief/mittel/hoch,  Arbeitshilfen  tief/mittel/hoch,  Beleuchtung
tief/mittel/hoch
1       0       0       4.167   0       0       0       0       0       0
```

The followings are the strings modified in the *Normbeleuchtungsstaerke.lib* file (in the original file, values are followed by tabs and not semicolons:

```
* Anzahl der Nutzungen für Primero-Sommer
29
* lfd. Nr. für interne Programmierung   Nennbeleuchtungsstärke[lx]   Name für Oberflächen
1      0     Einzelbüro
```

The following is the code modified in the *defaults.nml* file:

```
*-------------------------------------------------------------------------------------
*This file has been modified for the validation of Primero with ANSI/ASHRAE 140-2017 -
*LAST REVIEW GV 2020/05/06
*-------------------------------------------------------------------------------------


*-------------------------------------------------------------------------------------
*the following GROUNDTEMPERATURES_SURFACE were modified for the validation of Primero
*with ANSI/ASHRAE
*140-2017 - GV 2020/04/22 - new value 10
*-------------------------------------------------------------------------------------
*&GROUNDTEMPERATURES_SURFACE
*        January_Surface_Ground_Temperature = 4,
*        February_Surface_Ground_Temperature = 4,
*        March_Surface_Ground_Temperature = 6,
*        April_Surface_Ground_Temperature = 6,
*        May_Surface_Ground_Temperature = 10,
*        June_Surface_Ground_Temperature = 10,
*        July_Surface_Ground_Temperature = 15,
*        August_Surface_Ground_Temperature = 15,
*        September_Surface_Ground_Temperature = 14,
*        October_Surface_Ground_Temperature = 14,
*        November_Surface_Ground_Temperature = 8,
*        Dezember_Surface_Ground_Temperature = 8
*/


&GROUNDTEMPERATURES_SURFACE
        January_Surface_Ground_Temperature = 10,
        February_Surface_Ground_Temperature = 10,
        March_Surface_Ground_Temperature = 10,
        April_Surface_Ground_Temperature = 10,
        May_Surface_Ground_Temperature = 10,
        June_Surface_Ground_Temperature = 10,
        July_Surface_Ground_Temperature = 10,
        August_Surface_Ground_Temperature = 10,
        September_Surface_Ground_Temperature = 10,
        October_Surface_Ground_Temperature = 10,
        November_Surface_Ground_Temperature = 10,
        Dezember_Surface_Ground_Temperature = 10
/
```

```
*-------------------------------------------------------------------------------------
*the following GROUNDTEMPERATURES_DEEP were modified for the validation of Primero with
*ANSI/ASHRAE 140-2017 - GV 2020/04/22 - new value 10
*-------------------------------------------------------------------------------------
&GROUNDTEMPERATURES_DEEP
        January_Deep_Ground_Temperature = 10,
        February_Deep_Ground_Temperature = 10,
        March_Deep_Ground_Temperature = 10,
        April_Deep_Ground_Temperature = 10,
        May_Deep_Ground_Temperature = 10,
        June_Deep_Ground_Temperature = 10,
        July_Deep_Ground_Temperature = 10,
        August_Deep_Ground_Temperature = 10,
        September_Deep_Ground_Temperature = 10,
        October_Deep_Ground_Temperature = 10,
        November_Deep_Ground_Temperature = 10,
        Dezember_Deep_Ground_Temperature = 10
/

*-------------------------------------------------------------------------------------
*GROUNDTEMPERATURES_DEEP were modified for the validation of Primero with ANSI/ASHRAE
140-2017
*GV 2020/04/22 - THE FOLLOWING IS THE ORIGINAL DATA
*-------------------------------------------------------------------------------------
*&GROUNDTEMPERATURES_DEEP
*       January_Deep_Ground_Temperature = 16,
*       February_Deep_Ground_Temperature = 16,
*       March_Deep_Ground_Temperature = 16,
*       April_Deep_Ground_Temperature = 16,
*       May_Deep_Ground_Temperature = 16,
*       June_Deep_Ground_Temperature = 16,
*       July_Deep_Ground_Temperature = 16,
*       August_Deep_Ground_Temperature = 16,
*       September_Deep_Ground_Temperature = 16,
*       October_Deep_Ground_Temperature = 16,
*       November_Deep_Ground_Temperature = 16,
*       Dezember_Deep_Ground_Temperature = 16
*/
*-------------------------------------------------------------------------------------
*GROUNDTEMPERATURES_DEEP end of original data
*-------------------------------------------------------------------------------------

*-------------------------------------------------------------------------------------
```

```
*modified    window    construction    FOR    ASHRAE    140    "absorptance_Solar"    and
*"absorptance_Visible"
*FOLLOWED ENERGYPLUS INPUTS
*       originals:
*       Absorptance_Thermal = 0.9,
*       Absorptance_Solar = 0.7,
*       Absorptance_Visible = 0.7
*---------------------------------------------------------------------------------------

&MATERIAL_REGULAR_R
        Name(1) = 'Daem_Staenderwand',
        Roughness(1) = 'VeryRough',
        Thermal_Resistance(1) = .14,

        Name(2) = 'T_PH',
        Roughness(2) = 'VeryRough',
        Thermal_Resistance(2) = 1.08,

        Name(3) = 'T_Daem',
        Roughness(3) = 'VeryRough',
        Thermal_Resistance(3) = .66,

        Name(4) = 'T_EnEV',
        Roughness(4) = 'VeryRough',
        Thermal_Resistance(4) = .39,

        Name(5) = 'T_normal',
        Roughness(5) = 'VeryRough',
        Thermal_Resistance(5) = .12,

        Name(6) = 'T_metall',
        Roughness(6) = 'VeryRough',
        Thermal_Resistance(6) = .01,

        Absorptance_Thermal = 0.9,
        Absorptance_Solar = 0.6,
        Absorptance_Visible = 0.6
/

*---------------------------------------------------------------------------------------
*modified window construction FOR ASHRAE 140 "Clear 4" - FOLLOWED ENERGYPLUS INPUTS
*(this is the first window in Primero! 2-WSV,Krypton,U 1.1,     g 0.60, tvis 0.79
*see Name(101) - the following is the original one
```

```
*       Name(101) = '2003',
*       Schichten(101) = 3,
*       Layer(101,1) = 'Clear4',
*       Layer(101,2) = 'Krypton_12',
*       Layer(101,3) = 'OptimthermSN4',
*       Layer(101,4) = '',
*       Layer(101,5) = '',
*       Layer(101,6) = '',
*       Layer(101,7) = '',
*       Layer(101,8) = '',
*       Layer(101,9) = '',
*       Layer(101,10) = '',
*-------------------------------------------------------------------------------------

&CONSTRUCTION

        Name(101) = '2003',
        Schichten(101) = 3,
        Layer(101,1) = 'Clear4',
        Layer(101,2) = 'Luft_13',
        Layer(101,3) = 'Clear4',
        Layer(101,4) = '',
        Layer(101,5) = '',
        Layer(101,6) = '',
        Layer(101,7) = '',
        Layer(101,8) = '',
        Layer(101,9) = '',
        Layer(101,10) = '',

/

*-------------------------------------------------------------------------------------
*modified window construction FOR ASHRAE 140 "Clear 4" - FOLLOWED ENERGYPLUS INPUTS
*(this is the first window in Primero! 2-WSV,Krypton,U 1.1,     g 0.60, tvis 0.79
*Original was as it follows
*       Name(1) = 'Clear4',
*       Optical_Data_Type(1) = 'SpectralAverage',
*       Name_of_Window_Glass_Spectral_Data_Set(1) = 'CLEAR4_PGL',
*       Thickness(1) = 0.004,
*       Solar_Transmittance_Normal_Incidence(1) = 0.821,
*       Solar_Reflectance_Normal_Incidence_Front_Side(1) = 0.074,
*       Solar_Reflectance_Normal_Incidence_Back_Side(1) = 0.074,
*       Visible_Transmittance_Normal_Incidence(1) = 0.896,
```

```
*       Visible_Reflectance_Normal_Incidence_Front_Side(1) = 0.081,
*       Visible_Reflectance_Normal_Incidence_Back_Side(1) = 0.081,
*       IR_Transmittance_Normal_Incidence(1) = 0,
*       IR_Hemispherical_Emissivity_Front_Side(1) = 0.84,
*       IR_Hemispherical_Emissivity_Back_Side(1) = 0.84,
*       Conductivity(1) = 1,
*       Dirt_Correction_Factor(1) = 1,
*       Solar_Diffusing(1) = 'No',
*-------------------------------------------------------------------------------------
&MATERIAL_WINDOWGLASS
        Name(1) = 'Clear4',
        Optical_Data_Type(1) = 'SpectralAverage',
        Name_of_Window_Glass_Spectral_Data_Set(1) = ,
        Thickness(1) = 0.003175,
        Solar_Transmittance_Normal_Incidence(1) = 0.86156,
        Solar_Reflectance_Normal_Incidence_Front_Side(1) = 0.07846,
        Solar_Reflectance_Normal_Incidence_Back_Side(1) = 0.07846,
        Visible_Transmittance_Normal_Incidence(1) = 0.91325,
        Visible_Reflectance_Normal_Incidence_Front_Side(1) = 0.08200,
        Visible_Reflectance_Normal_Incidence_Back_Side(1) = 0.08200,
        IR_Transmittance_Normal_Incidence(1) = 0,
        IR_Hemispherical_Emissivity_Front_Side(1) = 0.84,
        IR_Hemispherical_Emissivity_Back_Side(1) = 0.84,
        Conductivity(1) = 1.06,
        Dirt_Correction_Factor(1) = 1,
        Solar_Diffusing(1) = 'No',

/

*-------------------------------------------------------------------------------------
*MATERIAL_WINDOWGAS was modified for the validation of Primero with ANSI/ASHRAE 140-
*2017
*GV 2020/04/22 - THE FOLLOWING IS THE ORIGINAL DATA
*       "Name(2) = 'Luft_12'" has been modified into "Name(2) = 'Luft_13'". the following
*is the original
*       Name(2) = 'Luft_12',
*       Gas_Type(2) = 'Air',
*       Thickness(2) = 0.012
*-------------------------------------------------------------------------------------

&MATERIAL_WINDOWGAS
        Name(1) = 'Krypton_12',
        Gas_Type(1) = 'Krypton',
        Thickness(1) = 0.012,
```

```
        Name(2) = 'Luft_13',

        Gas_Type(2) = 'Air',

        Thickness(2) = 0.013,


        Name(3) = 'Argon_12',

        Gas_Type(3) = 'Argon',

        Thickness(3) = 0.012,


        Name(4) = 'Argon_16',

        Gas_Type(4) = 'Argon',

        Thickness(4) = 0.016

/



*--------------------------------------------------------------------------------------

*modified window construction FOR ASHRAE 140 "Frame_Solar_Absorptance" and
*"Frame_Visible_Absorptance"

*FOLLOWED ANSI/ASHRAE 140 INPUTS & ENERGYPLUS INPUTS

*       originals:

*       Frame_Solar_Absorptance = 0.7,

*       Frame_Visible_Absorptance = 0.7,

*--------------------------------------------------------------------------------------



* GROUP - WindowShadingControl

&WINDOWFRAMEANDDIVIDER

        Frame_Width = 0.08,

        Frame_Outside_Projection = 0.04,

        Frame_Inside_Projection = 0.04,

        Ratio_of_Frame_Edge_Glass_Conductance_to_Center_Of_Glass_Conductance = 1,

        Frame_Solar_Absorptance = 0.6,

        Frame_Visible_Absorptance = 0.6,

        Frame_Thermal_Hemispherical_Emissivity = 0.9

/



*--------------------------------------------------------------------------------------

*the following lines in PEOPLE (fraction_radiant; Sens_Fraction) were modified for the
*validation of Primero with ANSI/ASHRAE 140-2017 - GV 2020/04/22

*the original lines were:

*       Fraction_radiant = .45, (now is .60)

*       Sens_Fraction = 'autocalculate',  (now is 1)

*--------------------------------------------------------------------------------------
```

```
* GROUP - Space Gains

&PEOPLE

        Name = 'Personen'

        Zone_Name = 'RAUM',

        Number_of_People = 1,

        Fraction_radiant = 0.60,

        People_Group_Name = 'Primero',

        Surface_Name = '',

        Work_Efficiency_ScheduleName = '',

        Clothing_Insulation_ScheduleName = '',

        Air_Velocity_ScheduleName = '',

        People_Calc_Method = 'people',

        People_Zone = 0,

        Zone_People = 0,

        Sens_Fraction = 1,

        Ashrae = 'Yes',

        MRT_Calculation_Type = 'ZoneAveraged'

/


*--------------------------------------------------------------------------------------

*VENTILATION_LUFTWECHSEL was modified for the validation of Primero with ANSI/ASHRAE
*140-2017

*GV 2020/04/22 - THE FOLLOWING IS THE ORIGINAL DATA

*       Vmin = 0.6,

*       Vmax_6bis22_Normal                    = 1,    Vmax_22bis6_Normal
        = 1.5,

*       Vmax_6bis22_Querlueftung        = 2,    Vmax_22bis6_Querlueftung        = 3,

*       Vmax_6bis22_Hoehendifferenz = 3,        Vmax_22bis6_Hoehendifferenz = 4.5

*--------------------------------------------------------------------------------------


&VENTILATION_LUFTWECHSEL

        Vmin = 0,

        Vmax_6bis22_Normal              = 0,    Vmax_22bis6_Normal              = 0,

        Vmax_6bis22_Querlueftung        = 0,    Vmax_22bis6_Querlueftung        = 0,

        Vmax_6bis22_Hoehendifferenz     = 0,    Vmax_22bis6_Hoehendifferenz     = 0

/
```

Appendix Chapter 05

Table A.4 – Construction settings for the simulation of the three buildings in DesignBuilder.

DESIGN BUILDER CONSTRUCTION SETTINGS - Components and Materials											
			Source	Term. Cond.	Density	Capacity	Thickness	U-value	Thermal Mass (ISO 13786)		
				λ	ρ	c	d	U	Δt	κ	κ
Model	Component	Material		(W/mK)	(kg/m³)	(J/kg K)	(m)	(W/m²K)	(h)	(kJ/m²K)	(Wh/m²K)
Typology 01 Manzil Zaynab Khatun	External Walls	Plaster Lightweight	A	0,16	600	1000	0,03	1,21	-18,38	38,74	10,76
		Limestone, semi hard	B	1,4	2000	1000	0,59				
		Lime sand render	B	0,8	1600	1000	0,015				
		Limestone hard	B	1,7	2200	1000	0,015				
	Internal Partitions	Plaster Lightweight	A	0,16	600	1000	0,03	0,95	-19,02	38,79	10,78
		Limestone, semi hard	B	1,4	2000	1000	0,59				
		Plaster Lightweight	A	0,16	600	1000	0,03				
	Roof	Timber Flooring	C	0,14	650	1200	0,02	2,05	-9,05	54,685	15,19
		Loose fill/powders - sand	C	1,74	2240	840	0,31				
		Stone limestone tiles	C	2,9	2750	840	0,02				
	Internal Floor	Timber Flooring	C	0,14	650	1200	0,02	1,67	-9,63	42,902	11,92
		Loose fill/powders - sand	C	1,74	2240	840	0,31				
		Stone limestone	C	2,9	2750	840	0,02				
	Ground Floor	Stone limestone	C	2,9	2750	840	0,05	1,72	-19,05	66,413	18,45
		Clay underfloor	D	1,5	1500	2085	0,5				
Typology 02 Hamed Said House	External Walls	Plaster lightweight	A	0,16	600	1000	0,02	0,77	-20,77	40,44	11,23
		PhD adobe wall	E	0,59	1400	1000	0,56				
		Lime sand render	B	0,8	1600	1000	0,02				
	Internal Partitions	Plaster Lightweight	A	0,16	600	1000	0,03	0,63	-22,17	35,82	9,95
		PhD adobe wall	E	0,59	1400	1000	0,56				
		Plaster Lightweight	A	0,16	600	1000	0,03				
	Roof	Plaster lightweight	A	0,16	600	1000	0,02	1,2	-11,79	47,201	13,11
		PhD adobe wall	E	0,59	1400	1000	0,31				
		Lime sand render	B	0,8	1600	1000	0,02				
	Ground Floor	Stone limestone	C	2,9	2750	840	0,05	1,61	-19,05	66,413	18,45
		Clay underfloor	D	1,5	1500	2085	0,5				
Typology 03 Abdullah's Building	External Walls	Plaster Lightweight	A	0,16	600	1000	0,005	2,23	-4,76	58,962	16,38
		Zement Sand Mörtel	B	1	1600	1000	0,025				
		Brickwork	C	0,62	1700	800	0,125				
	Internal P.	Brickwork	C	0,62	1700	800	0,125	2,16	-4,24	59,527	16,54
	Roof	Concrete, High density	B	2	2400	1000	0,150	2,55	-7,75	108,72	30,20
		Bitumen, felt/sheet	B	0,23	1100	1000	0,020				
		Loose fill/powders - sand	C	1,74	2240	840	0,050				
		Zement Sand Mörtel	B	1	1600	1000	0,025				
		Concrete tiles	B	1,50	2100	1000	0,025				
	Internal F.	Concrete, High density	B	2	2400	1000	0,15	2,9	-5,19	68,67	19,08
	Ground Floor	Stone limestone	C	2,9	2750	840	0,02	1,43	-23,66	61,762	17,16
		Zement Sand Mörtel	B	1	1600	1000	0,02				
		Loose fill/powders - sand	C	1,74	2240	840	0,06				
		Concrete, High density	B	2	2400	1000	0,15				
		Clay underfloor	D	1,5	1500	2085	0,5				
Legend:	Source: A=DesignBuilder; B=ISO DIN 10456; C=CIBSE; D=BS EN 12524; E= Primero U-Wert (ISO DIN 10456) Thermal Mass (ISO 13786): Δt=time shift periodic thermal transmittance; κ =Internal Heat Capacity										

Table A.5 – Detailed settings used for Sensibility Analysis.

Variable	Options	Material	Thickness d (m)	U-value U (W/m²K)	Int. Heat Capacity κ (KJ/m²K)
External wall construction U-Value	**PhD_SA_EW_01_Insulated_heavy_33cm_U0,25**	Brickwork	0,105	0,25	134,80
		XPS Extr. Polystyrene	0,12		
		Concrete Medium	0,1		
		Gypsum Plastering	0,013		
	PhD_SA_EW_02_Adobe_60cm_U0,77	Plaster lightweight	0,02	0,77	124,00
		PhD adobe wall	0,56		
		Lime sand render	0,02		
	PhD_SA_EW_03_Limestone_65cm_U1,21	Plaster Lightweight	0,03	1,21	158,00
		Limestone, semi hard	0,59		
		Lime sand render	0,015		
		Limestone hard	0,015		
	PhD_SA_EW_04_Brickwork_15cm_U2,23	Plaster Lightweight	0,005	2,23	138,20
		Zement Sand Mörtel	0,025		
		Brickwork	0,125		
Flat roof construction U-Value	**PhD_SA_ROOF_01_Insulated_18cm_U0,481**	Asphalt	0,019	0,481	108,00
		Fibreboard	0,013		
		XPS Extr. Polystyrene	0,05		
		Cast Concrete	0,1		
	PhD_SA_ROOF_02_Adobe_35cm_U1,2	Plaster lightweight	0,02	1,2	124,00
		PhD adobe wall	0,31		
		Lime sand render	0,02		
	PhD_SA_ROOF_03_stoneandsand_35cm_U2,05	Timber Flooring	0,02	2,05	166,13
		Loose fill/powders - sand	0,31		
		Stone limestone tiles	0,02		
	PhD_SA_ROOF_04_Concrete_Uninsulated_27cm_U2,55	Concrete, High density	0,150	2,55	240,00
		Bitumen, felt/sheet	0,020		
		Loose fill/powders - sand	0,050		
		Zement Sand Mörtel	0,025		
		Concrete tiles	0,025		
Partition construction U-Value	**PhD_SA_IP_01_Adobe_62cm_U0,63**	Plaster Lightweight	0,03	0,63	116,00
		PhD adobe wall	0,56		
		Plaster Lightweight	0,03		
	PhD_SA_IP_02_Limestone_65cm_U0,95	Plaster Lightweight	0,03	0,95	158,00
		Limestone, semi hard	0,59		
		Plaster Lightweight	0,03		
	PhD_SA_IP_03_Adobe_25cm_U1,463	Adobe 15 cm	0,25	1,463	140,00
	PhD_SA_IP_04_Brickwork_12,5cm_U2,16	Brickwork	0,125	2,16	136,00
Glazing	**Double glazing, clear, LoE, argon-filled**			1,7/3,3	
	Single glazing no shading			5,7/3,3	
WWR	**Windows to Wall Ratio (5-40%)**	8 steps (5;10;15;20;25;30;35;40%)			
Local shading	**No Shading / Overhang 1,5 m**	6 steps (0;0,25;0,5;0,75;1,00;1,25;1,5 m)			
Natural Ventilation Rate	**Ventilation rate from 0 to 10 ac/h (5 steps)**	5 steps (0;2;4;6;8;10 ac/h)			
Ventilation Setpoint	**Ventilation setpoint 20**	Continuous: 20 +/- 3			

Appendix Chapter 06

Table A.6 – Specification of construction variables used for Sensitivity Analysis and Optimisation (1/2). Data source for estimated costs: A=Ali et al, (2017); B=CAPMAS,(2021); C=Abdellatif, (2018); D=Abouaiana, (2021); E=Estimated assumption by the author.

Component	DB Name	Material	Term. Cond. λ (W/mK)	Density ρ (kg/m³)	Capacity c (J/kg K)	Thickness d (m)	U-Value (ISO 13786) U (W/m²K)	U-value (DB) U (W/m²K)	Cost Estimate Component EGP (EGP / m2)	Cost Estimate Material EGP (EGP / m2)	Source
External Walls (from outside [top] to inside [bottom])	SA_EW_ClayBrick_simple	Brickwork	0,62	1700	800	0,125	2,115	2,115	**105**	60	A.B
		Plaster Lightweight	0,16	600	1000	0,013				45	D
	SA_EW_ClayBrick_double	Brickwork	0,62	1700	800	0,125	1,32	1,213	**165**	60	A.B
		Air	0,15 (R-Value)								
		Brickwork	0,62	1700	800	0,125				60	A.B
		Plaster Lightweight	0,16	600	1000	0,013				45	D
	SA_EW_ClayBrick_double_EPS	Brickwork	0,62	1700	800	0,125	0,475	0,444	**240**	60	A.B
		Air	0,15 (R-Value)			0,01					
		EPS Expanded Polystyrene	0,035	25	1400	0,05				75	D
		Brickwork	0,62	1700	800	0,125				60	A.B
		Plaster Lightweight	0,16	600	1000	0,013				45	D
	SA_EW_HollowBrick_simple	Hollow Clay Brick	0,66	1500	1000	0,125	2,171	2,171	**115**	70	C
		Plaster Lightweight	0,16	600	1000	0,013				45	D
	SA_EW_HollowBrick_double	Hollow Clay Brick	0,66	1500	1000	0,125	1,54	1,25	**185**	70	C
		Air	0,15 (R-Value)			0,01					
		Hollow Clay Brick	0,66	1500	1000	0,125				70	C
		Plaster Lightweight	0,16	600	1000	0,013				45	D
	SA_EW_HollowBrick_double_EPS	Hollow Clay Brick	0,66	1500	1000	0,125	0,481	0,449	**260**	70	C
		Air	0,15 (R-Value)								
		EPS Expanded Polystyrene	0,035	25	1400	0,05				75	D
		Hollow Clay Brick	0,66	1500	1000	0,125				70	C
		Plaster Lightweight	0,16	600	1000	0,013				45	D
	SA_EW_StabilisedSoilBrick_simple (Stabilised Soil Brick – PhD Adobe	Stabilised Soil Brick	0,59	1400	1000	0,125	2,07	2,07	**76**	31	A
		Plaster Lightweight	0,16	600	1000	0,013				45	D
	SA_EW_StabilisedSoilBrick_double	Stabilised Soil Brick	0,66	1500	1000	0,125	1,439	1,183	**107**	31	A
		Air	0,15 (R-Value)			0,01					
		Stabilised Soil Brick	0,66	1500	1000	0,125				31	A
		Plaster Lightweight	0,16	600	1000	0,013				45	D
	SA_EW_StabilisedSoilBrick_double_EPS	Stabilised Soil Brick	0,66	1500	1000	0,125	0,471	0,44	**182**	31	A
		Air	0,15 (R-Value)			0,01					
		EPS Expanded Polystyrene	0,035	25	1400	0,05				75	D
		Stabilised Soil Brick	0,66	1500	1000	0,125				31	A
		Plaster Lightweight	0,16	600	1000	0,013				45	D

Note: specifications of "air" (as material) given in DesignBuilder is not consistent with the one specified in the EN ISO 10456. Therefore U-Values might be slightly different. See also the note in Chapter 6.7

Table A.6 – Specification of construction variables used for Sensitivity Analysis and Optimisation (1/2). Data source for estimated costs: A=Ali et al, (2017); B=CAPMAS,(2021); C=Abdellatif, (2018); D=Abouaiana, (2021); E=Estimated assumption by the author. (Continuation).

Component	DB Name	Material	Term. Cond. λ (W/mK)	Density ρ (kg/m³)	Capacity c (J/kg K)	Thickness d (m)	U-Value (ISO 13786) U (W/m²K)	U-value (DB) U (W/m²K)	Cost Estimate Component EGP (EGP / m2)	Cost Estimate Material EGP (EGP / m2)	Source
Internal Partitions	SA_IP_ClayBrick	Brickwork	0,62	1700	800	0,125	2,166	2,16	**60**	60	A.B
	SA_IP_HollowBrick	Hollow Clay Brick	0,66	1500	1000	0,125	2,225	2,225	**70**	70	C
	SA_IP_StabilisedSoilBrick	Stabilised Soil Brick	0,59	1400	1000	0,125	2,119	2,119	**31**	31	A
Roof (from inside [top] to outside [bottom])	SA_ROOF_Basis	Concrete, High density	2	2400	1000	0,150				525	D
		Bitumen, felt/sheet	0,23	1100	1000	0,020				75	E
		Loose fill/sand	1,74	2240	840	0,050	2,549	2,549	**700**	10	B
		Zement Sand Mörtel	1	1600	1000	0,025				60	D
		Concrete tiles	1,50	2100	1000	0,025				30	B
	SA_ROOF_EPS_50	Concrete, High density	2	2400	1000	0,150				525	D
		Cast Concrete	1,13	2000	1000	0,050				100	E
		Vapor Barrier	0,21			0,005	0,579	0,517	**755**	75	E
		EPS Expanded Polystyrene	0,035	25	1400	0,05				75	D
		Concrete tiles	1,50	2100	1000	0,025				30	B
	SA_ROOF_EPS_100	Concrete, High density	2	2400	1000	0,150				525	D
		Cast Concrete	1,13	2000	1000	0,050				100	E
		Vapor Barrier	0,21			0,005	0,317	0,297	**880**	75	E
		EPS Expanded Polystyrene	0,035	25	1400	0,1				150	D
		Concrete tiles	1,50	2100	1000	0,025				30	B
Internal Floors	SA_IF_15	Concrete, High density	2	2400	1000	0,15	2,985	3,279	**525**	525	D
	SA_IF_12	Concrete, High density	2	2400	1000	0,12	3,12	3,448	**420**	420	D
Ground Floor (from inside [top] to outside [bottom])	SA_GF_Basis	Stone limestone	2,9	2750	840	0,02				300	B
		Zement Sand Mörtel	1	1600	1000	0,02				60	D
		Loose fill/sand	1,74	2240	840	0,06	1,43	1,43	**961**	10	B
		Concrete, High density	2	2400	1000	0,15				525	D
		Clay underfloor	1,5	1500	2085	0,5				70	B
	SA_GF_Ventilated_Traditional	Stone limestone	2,9	2750	840	0,02				300	B
		Zement Sand Mörtel	1	1600	1000	0,02				60	D
		Protection Membrare (Vapor	0,21			0,005				75	E
		Concrete, High density	2	2400	1000	0,12	1,47	0,842	**1100**	420	D
		Brickwork Slab	2	2400	1000	0,06				175	D
		Air	0,23			0,3				0	
		Clay underfloor	1,5	1500	2085	0,5				70	B
	SA_GF_Igloo_Modern_Insulated	Stone limestone	2,9	2750	840	0,02				300	B
		Zement Sand Mörtel	1	1600	1000	0,02				60	D
		Cast Concrete	1,13	2000	1000	0,050				100	E
		EPS Expanded Polystyrene	0,035	25	1400	0,05	0,5603	0,449	**995**	75	D
		Protection Membrare (Vapor	0,21			0,005				75	E
		Concrete, High density	2	2400	1000	0,06				210	D
		Air	0,23			0,45				0	
		Concrete, High density	2	2400	1000	0,05				175	D
Windows	SA_WIN_Single	Glazing Single (and Frame)					5,7 (3,3)	3,3	**1750**	1750	D
	SA_WIN_Double	Glazing Double (and Frame)					1,76 (3,3)	5,7	**2200**	2200	C
	SA_WIN_Triple	Glazing Triple (and Frame)					0,98 (3,3)	1,76	**4500**	4500	C

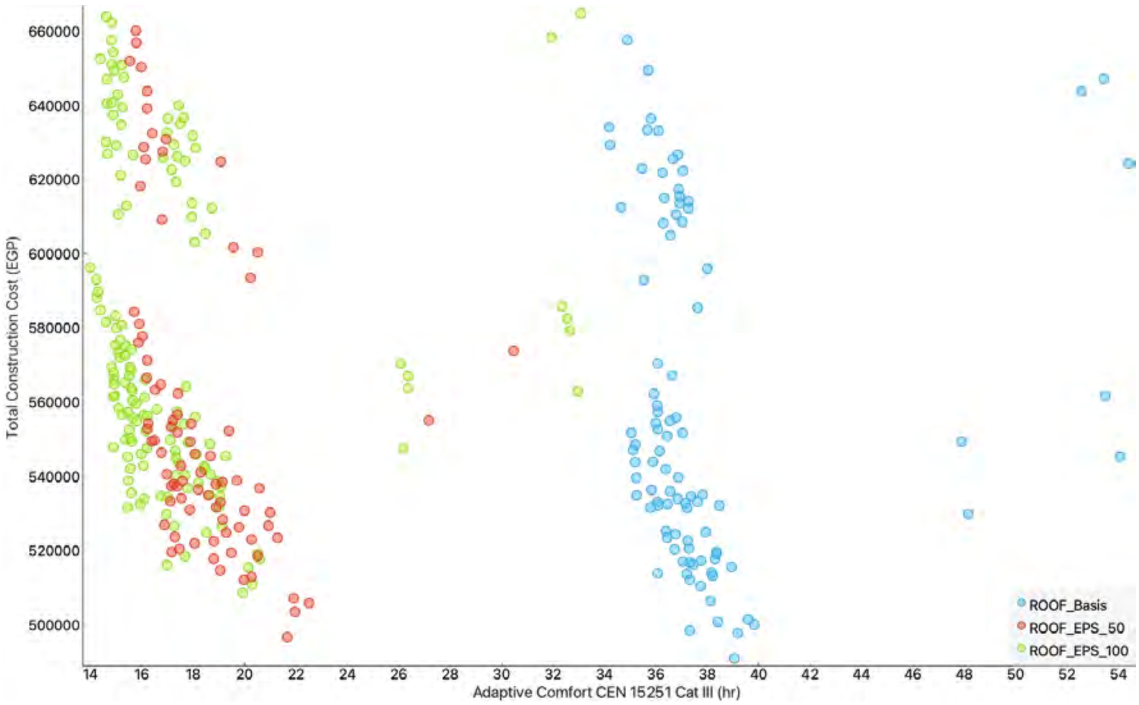

Figure A.11 – Abdullah's building optimisation results – Comfort and cost – Category: flat roof construction.

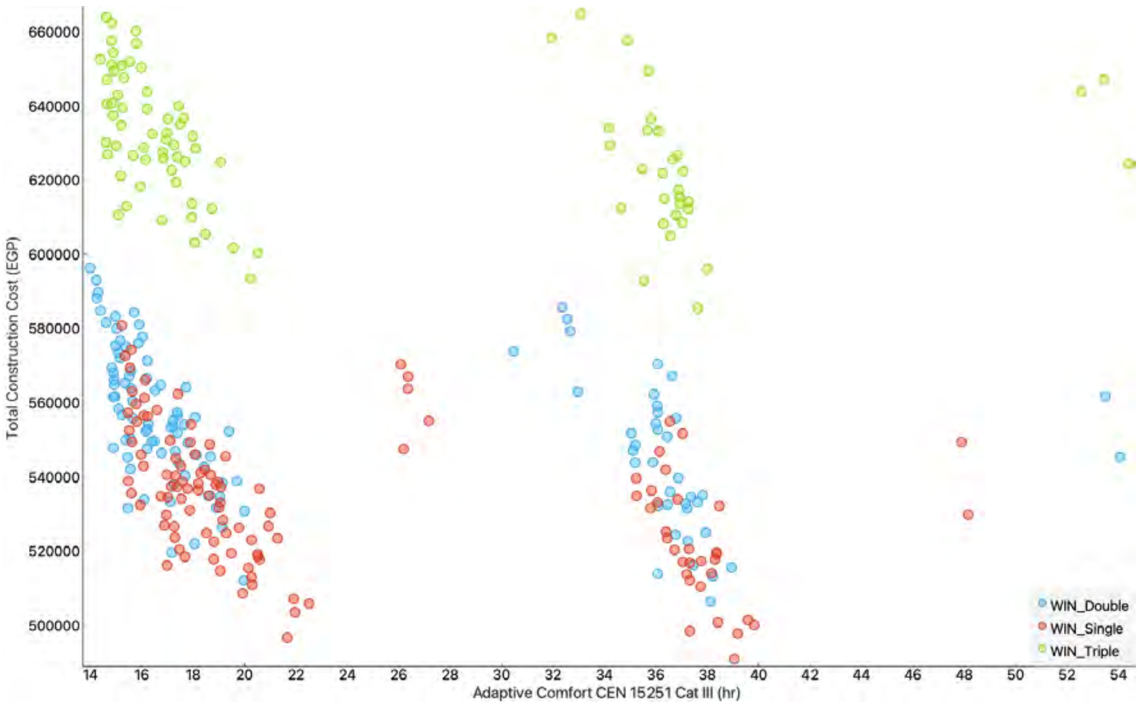

Figure A.12 – Abdullah's building optimisation results – Comfort and cost – Category: glazing.

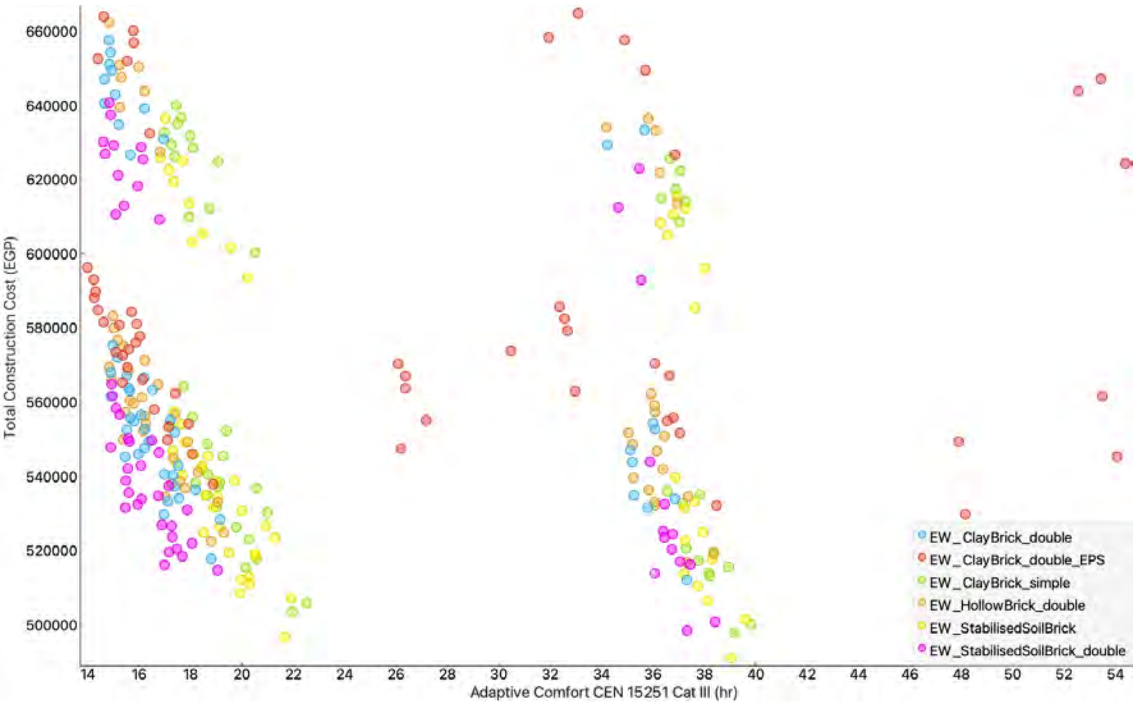

Figure A.13 – Abdullah's building optimisation results – Comfort and cost – Category: external walls construction.

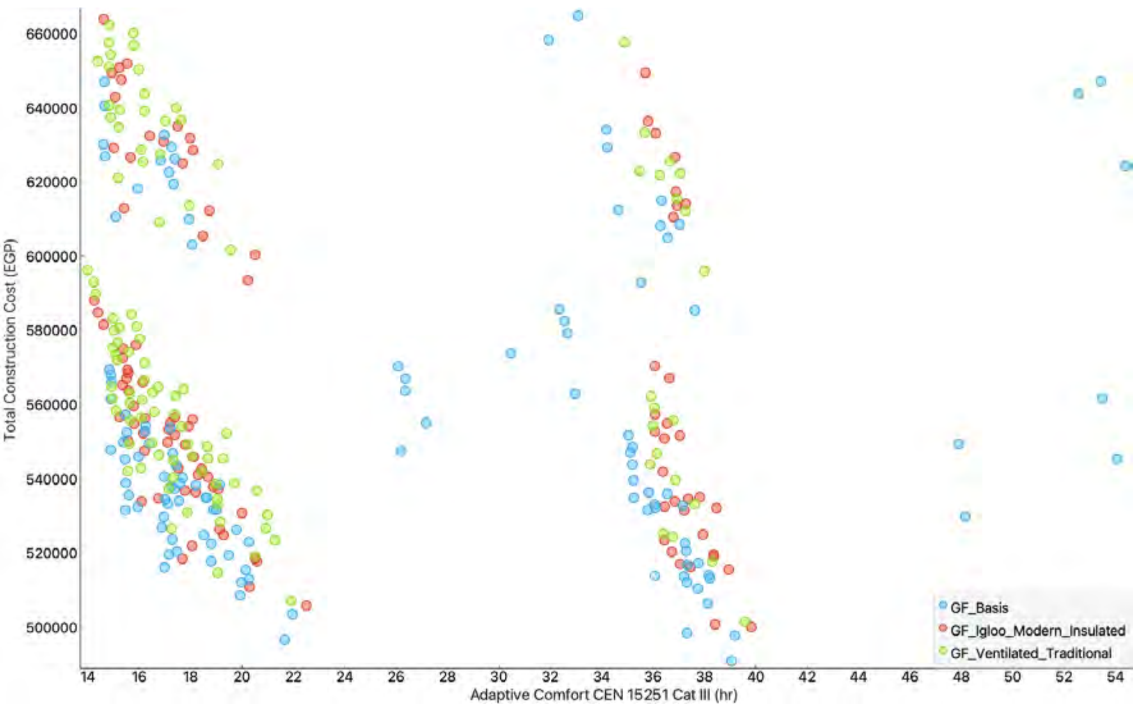

Figure A.14 – Abdullah's building optimisation results – Comfort and cost – Category: ground floor construction.

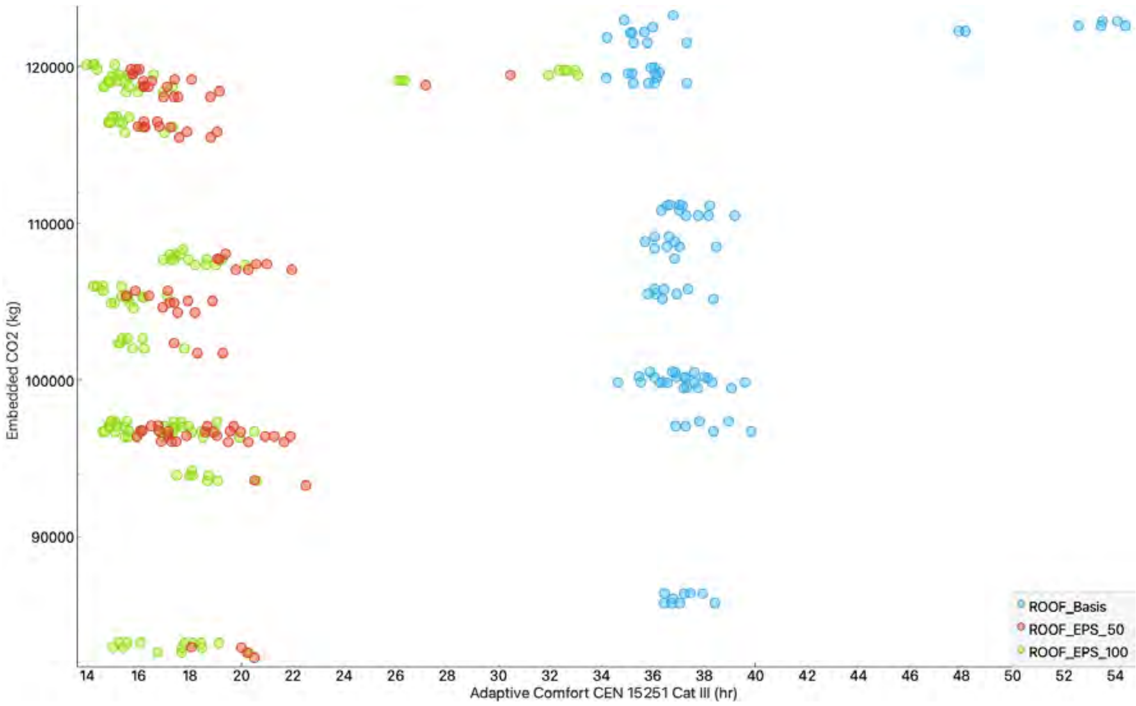

Figure A.15 – Abdullah's building optimisation results – Comfort and CO_2 – Category: flat roof construction.

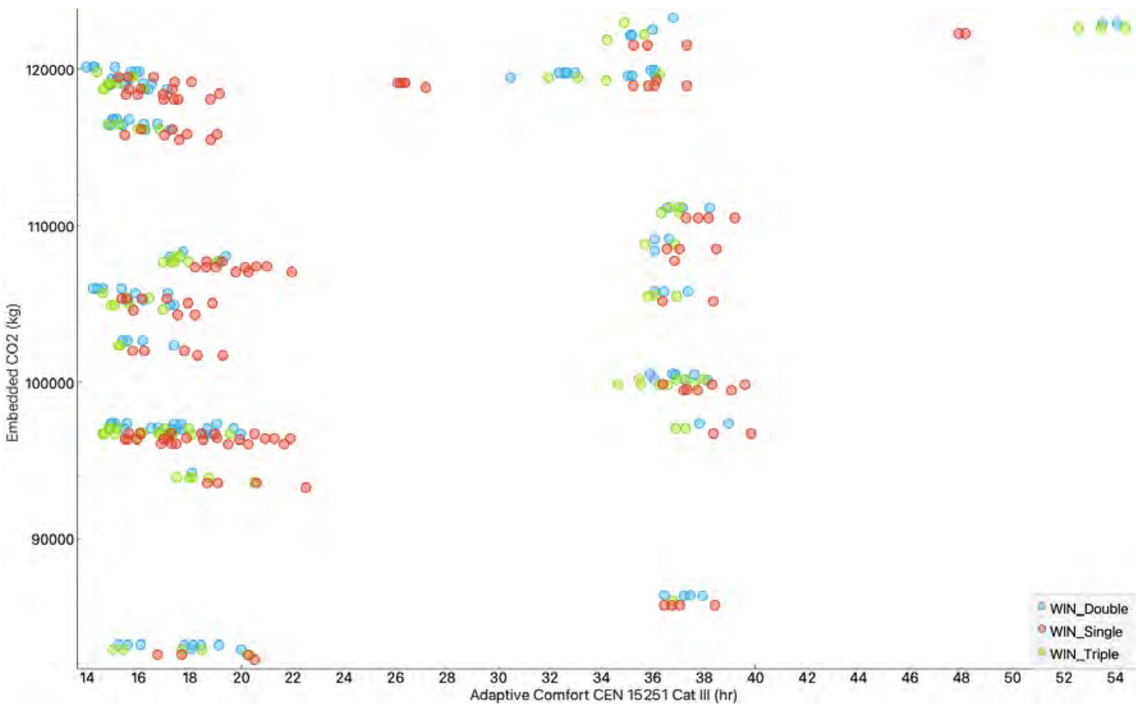

Figure A.16 – Abdullah's building optimisation results – Comfort and CO_2 – Category: glazing.

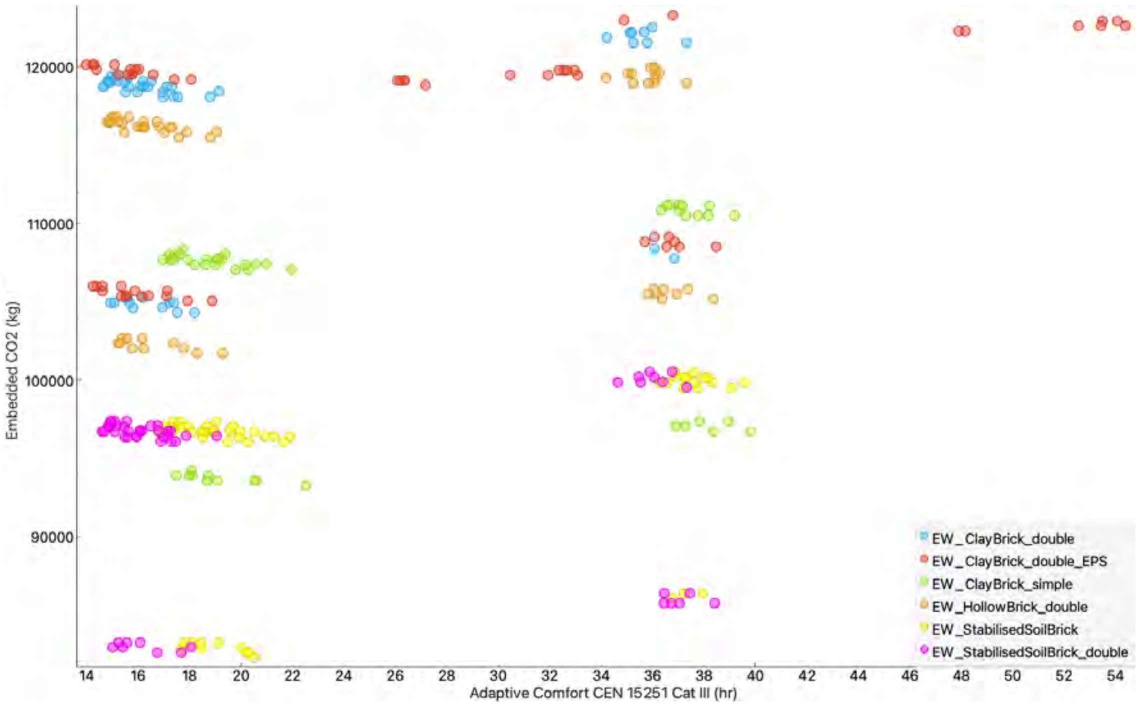

Figure A.17 – Abdullah's building optimisation results – Comfort and CO_2 – Category: external walls construction.

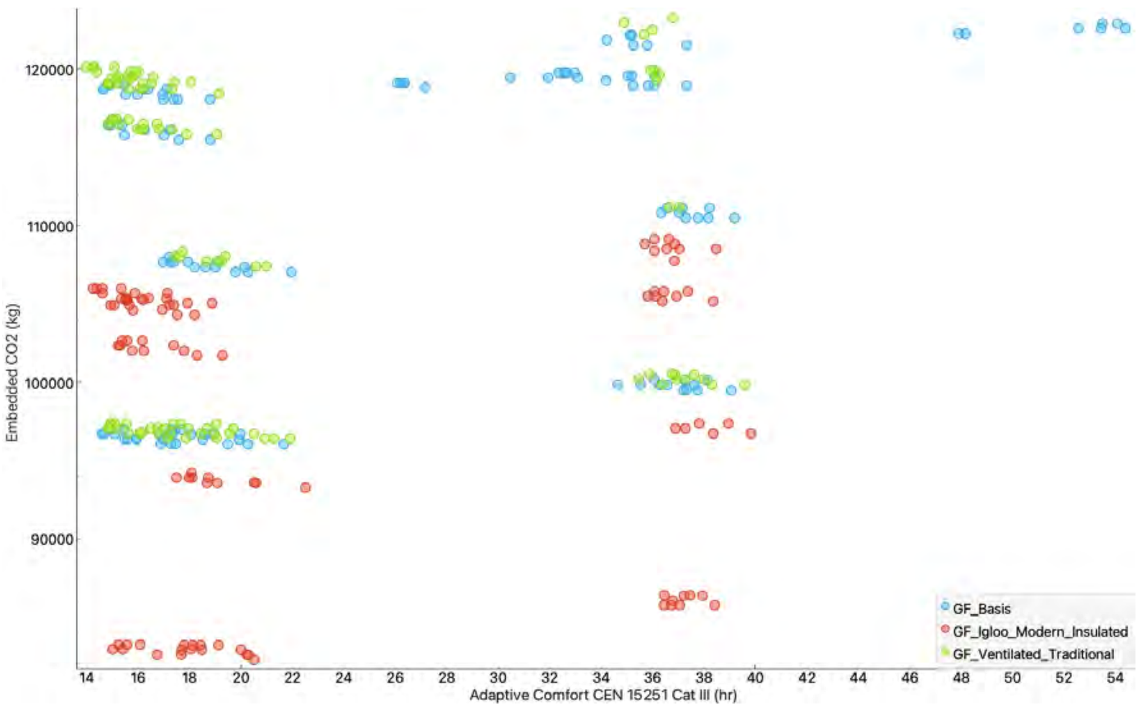

Figure A.18 – Abdullah's building optimisation results – Comfort and CO_2 – Category: ground floor construction.

Table A.7 – Selection of iterations within optimisation results.

FREE FLOAT MODE YEARLY RESULTS TEMPERATURES		Abdullah's Building Optimisation Results (Selection) IT-060	IT-098-SQ	UT-120	IT-220	IT-283
Total Construction Cost (x1.000 EGP)		▼491	▼498	▲596	▼497	►532
Embedded CO_2 (t)		▼99	►109	▲119	▼95	▼97
Comfortable Hours (Year; Max = 8760 hrs.)		▼6279	▼6250	▲7730	▼6555	▲7265
Comfortable Hours (Year; Max = 100%)		72%	71%	88%	75%	83%
Percentage of Monthly Comfortable Hours (18°-29°C)	January	3%	2%	45%	6%	16%
	February	54%	53%	91%	56%	73%
	March	91%	91%	100%	92%	96%
	April	100%	99%	100%	100%	100%
	May	99%	99%	100%	99%	100%
	June	87%	86%	100%	91%	99%
	July	59%	58%	83%	65%	84%
	August	39%	39%	56%	46%	59%
	September	86%	86%	95%	90%	96%
	October	100%	100%	100%	100%	100%
	November	90%	89%	99%	92%	97%
	December	55%	54%	92%	62%	75%
Selected Variables	External Wall Construction	Stabilised Soil Bricks	Clay Bricks Single (SQ)	Clay Bricks Double + EPS	Stabilised Soil Bricks	Stabilised Soil Bricks Double
	Flat Roof Construction	Basic Roof (SQ)	Basic Roof (SQ)	Basic Roof + EPS 100	Basic Roof + EPS 50	Basic Roof + EPS 100
	Ground Floor Construction	Basic GF (SQ)	Basic GF (SQ)	Ventilated GF	Basic GF (SQ)	Basic GF (SQ)
	Glazing Template	Single Glazing (SQ)	Single Glazing (SQ)	Double Glazing	Single Glazing (SQ)	Double Glazing
	Overhang	No shading (SQ)	No shading (SQ)	1,5 m	No shading (SQ)	No shading (SQ)

Table A.8 – Selected materials and results of the optimum model.

Abdullah's Building Optimum Results			Selected Materials
Total Construction Cost (x1.000 EGP)		517	
Embedded CO2 (t)		49	**External Wall Construction:**
Comfortable Hours (Year; Max = 8760 hrs.)		8010	Stabilised Soil Bricks Double + EPS
Comfortable Hours (Year; Max = 100%)		91%	**Glazing Template_**
Percentage of Monthly Comfortable Hours (18°-29°C)	January	42%	Double Glazing
	February	87%	**Flat Roof Construction:**
	March	99%	Basic Roof + EPS 100
	April	100%	**Ground Floor Construction:**
	May	100%	Basic GF (sand filling instead of clay blocks)
	June	100%	**Internal Partitions:**
	July	99%	Stabilised Soil Bricks Double
	August	78%	**Internal floor:**
	September	100%	12 cm concrete
	October	100%	**Shading Template:**
	November	99%	No shading (SQ)
	December	92%	

Table A.9 – Selection of iterations within optimisation results – Construction costs.

Construction	IT-060	IT-098-SQ	IT-120	IT-220	IT-283
	Construction Costs (EGP)				
Roof	84.645	84.645	102.326	90.380	102.326
Intermediate Floor	186.821	186.821	186.821	186.821	186.821
Ground Floor	75.207	75.207	85.729	75.207	75207
External Wall	17.887	24.711	56.483	17.887	25181
Internal Partition	43.824	43.824	43.824	43.824	43824
Glazing	62.037	62.037	77.504	62.037	77.504
Overhang	0	0	22.782	0	0
Internal Door	20.444	20.444	20.444	20.444	20444
SUM	**490.865**	**497.689**	**595.913**	**496.600**	**531.307**

Table A.10 – Selection of iterations within optimisation results – Environmental costs.

Material	IT-060	IT-098-SQ	IT-120	IT-220	IT-283
	Embodied Carbon (kgCO2)				
Plaster Lightweight	220	220	220	220	220
Loose fill/powders - sand	482	482	59	268	268
Stone limestone	86	86	86	86	86
Clay underfloor	12.859	12.859	12.859	12.859	12.859
Stabilized Soil Bricks	1.133	0	0	1.133	2.266
Cement Sand Mortar	1.400	1.400	673	673	673
Brickwork	34.146	45.148	57.900	34.146	34.146
E. concrete, High density	42.002	42.002	40.866	42.002	42.032
Bitumen, felt/sheet	4.555	4.555	981	981	981
Concrete tiles	1.407	1.407	1.407	1.407	1.407
EPS Expanded Polystyrene	0	0	1.333	299	597
Single Glazing	638	638	0	638	0
Double Glazing	0	0	1.280	0	1.280
Overhang	0	0	1.718	0	0
SUM	**98.928**	**108.797**	**119.382**	**94.711**	**96.815**

Table A.11 – Optimum – Construction costs.

Construction	OPTIMUM
	Costs (EGP)
Roof	107.353
Intermediate Floor	150.247
Ground Floor	75.207
External Wall	42.856
Internal Partition	45.402
Glazing	76.776
Overhang	0
Internal Door	19.482
SUM	**517.323**

Table A.12 – Optimum – Environmental costs.

Material	OPTIMUM
	Emb. Carbon
Plaster Lightweight	220
Loose fill/powders - sand	1.955
Stone limestone	86
Clay underfloor	0
Stabilized Soil Bricks	10.162
Cement Sand Mortar	474
Brickwork	0
E. concrete, High density	37.726
Bitumen, felt/sheet	0
Concrete tiles	1.409
EPS Expanded Polystyrene	1.498
Single Glazing	0
Double Glazing	1.269
Overhang	0
SUM	**54.799**

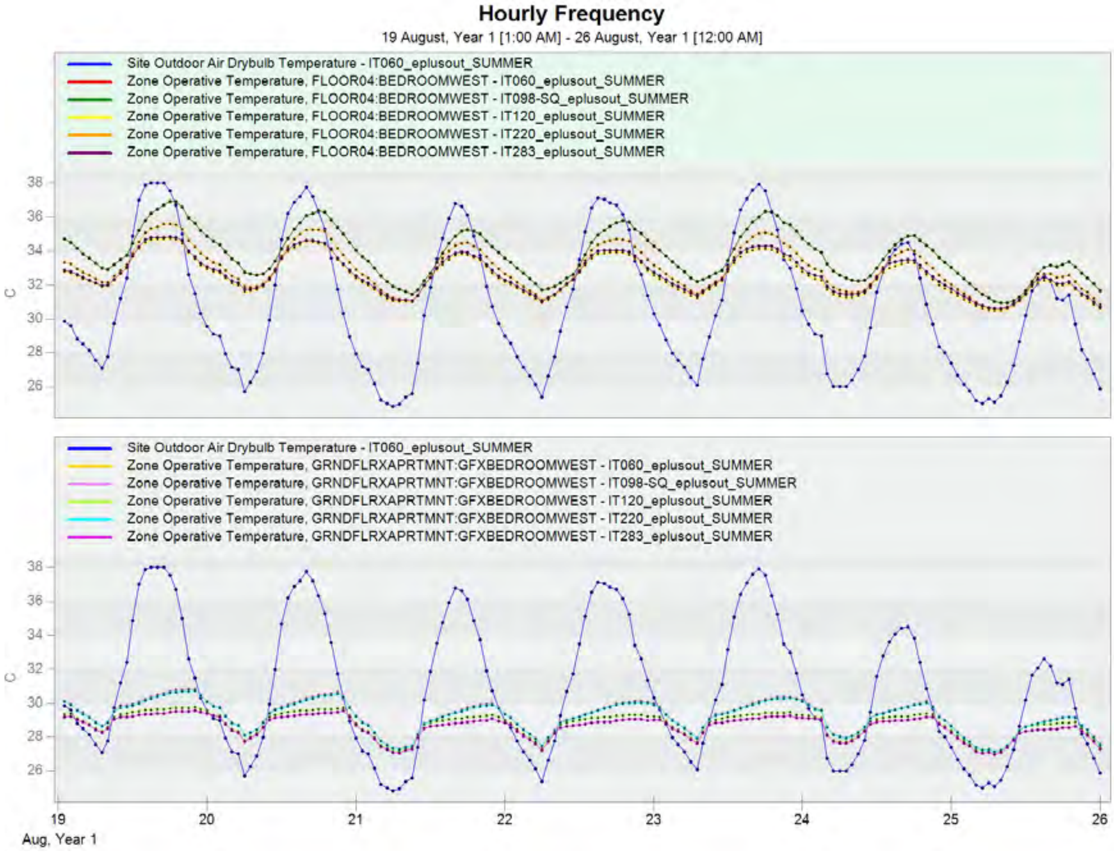

Figure A.19 – Comparison of hourly hours of the five iterations – Summer week – Graphic above represents T_O in the fourth floor (bedroom west), the one below represents T_O in the ground floor (bedroom West) - IT060 and IT098-SQ appear as one line because they have practically the same output – differences are below 0,1°C.

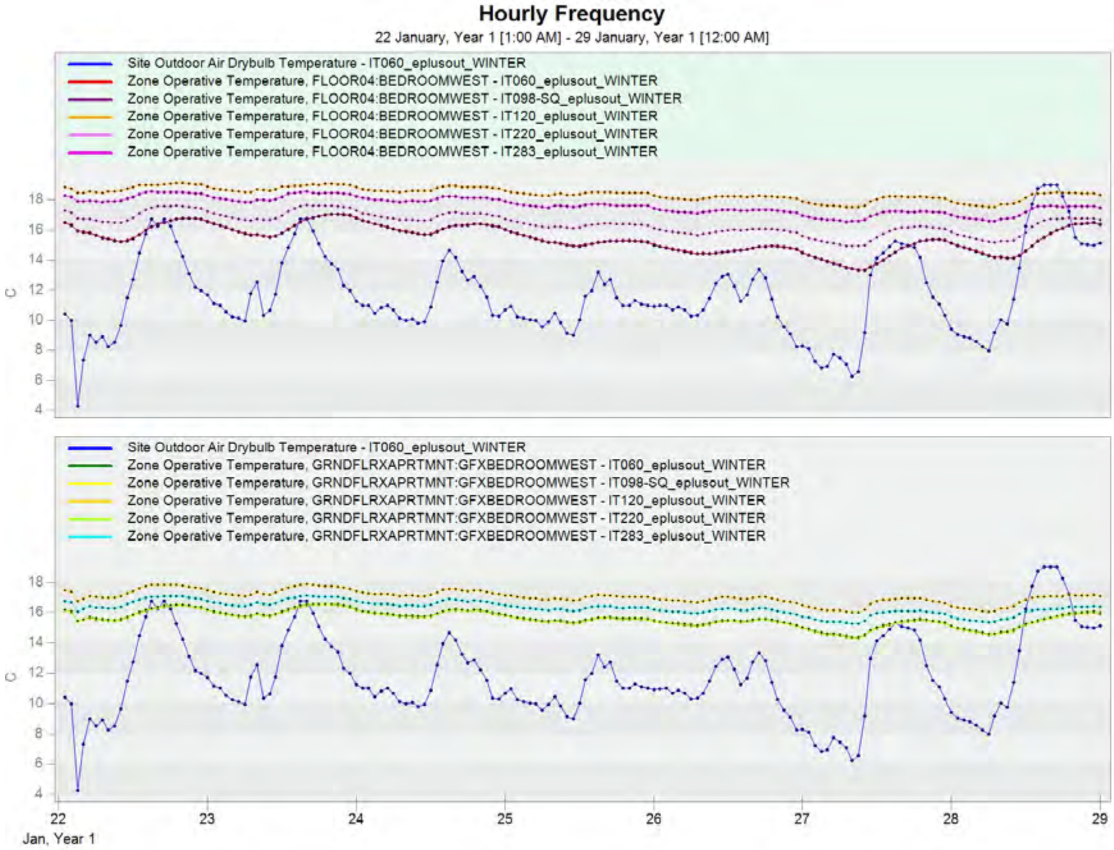

Figure A.20 – Comparison of hourly hours of the five iterations – Winter week – Graphic above represent T_O in the fourth floor (bedroom west), the one below represents T_O in the ground floor (bedroom West) - IT060 and IT098-SQ appear as one line only because they have practically the same output – differences are below 0,1°C.

Table A.13 – Abdullah's retrofit – The studied options are marked in grey.

FREE FLOAT MODE YEARLY RESULTS TEMPERATURES		Abdullah's Building Retrofit				
		IT-098-SQ	**A**	**B**	**C**	**D**
Total Construction Cost (x1.000 EGP)		**498**	**520**	**500**	**513**	**539**
Embedded CO2 (t)		**109**	**119**	**95**	**109**	**106**
Comfortable Hours (Year; Max = 8760 hrs.)		**6250**	**6657**	**6440**	**6354**	**6795**
Comfortable Hours (Year; Max = 100%)		**71%**	**76%**	**74%**	**73%**	**78%**
Percentage of Monthly Comfortable Hours (18°-29°C)	January	2%	7%	3%	3%	7%
	February	53%	57%	50%	55%	59%
	March	91%	93%	89%	91%	93%
	April	99%	100%	100%	100%	100%
	May	99%	99%	99%	99%	100%
	June	86%	93%	91%	88%	95%
	July	58%	67%	66%	60%	73%
	August	39%	48%	47%	41%	53%
	September	86%	91%	90%	88%	94%
	October	100%	100%	100%	100%	100%
	November	89%	92%	90%	90%	93%
	December	54%	65%	56%	57%	66%
Selected Variables	External Wall Construction	Clay Bricks Single (SQ)	Clay Bricks Single (SQ)	Clay Bricks Single (SQ)	Clay Bricks Single (SQ)	Clay Bricks Single (SQ)
	Flat Roof Construction	Basic Roof (SQ)	Basic Roof + EPS 100	Basic Roof reflective mat	Basic Roof (SQ)	Basic Roof + EPS 100 + refl mat
	Ground Floor Construction	Basic GF (SQ)	Basic GF (SQ)	Basic GF (SQ)	Basic GF (SQ)	Basic GF (SQ)
	Glazing Template	Single Glazing (SQ)	Single Glazing (SQ)	Single Glazing (SQ)	Double Glazing	Double Glazing
	Overhang	No shading (SQ)	No shading (SQ)	No shading (SQ)	No shading (SQ)	No shading (SQ)

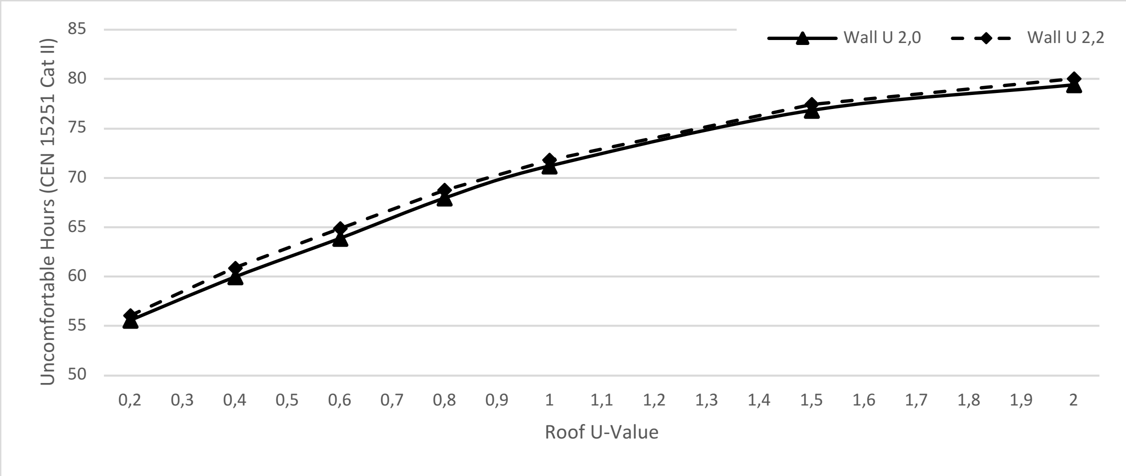

Figure A.21 – Scenario A - South. Parametric analysis of roof and wall U-Value (uncomfortable hours).

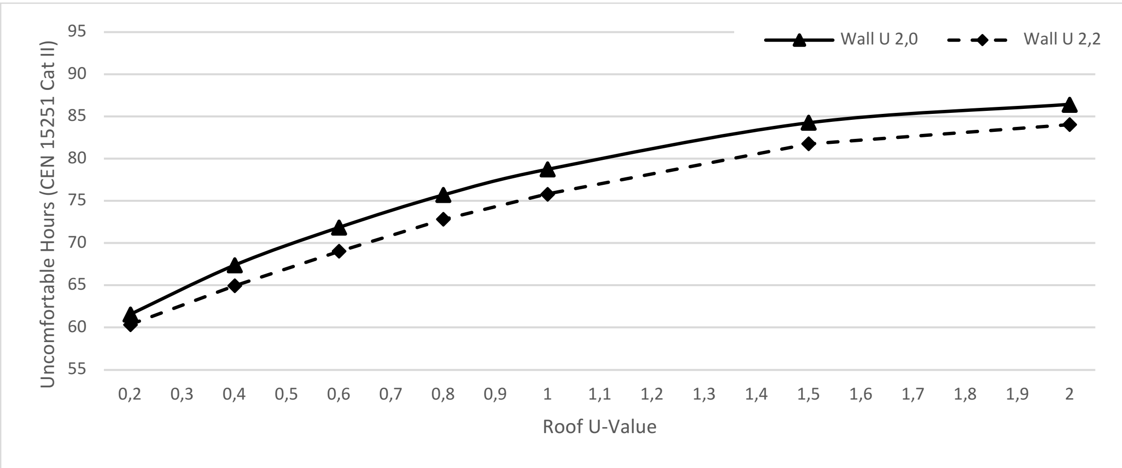

Figure A.22 – Scenario B - South. Parametric analysis of roof and wall U-Value (uncomfortable hours).

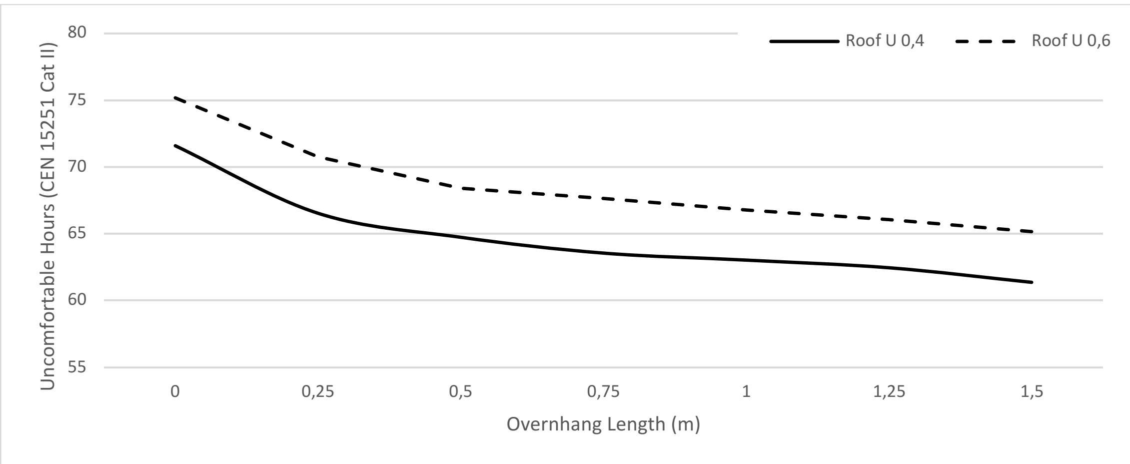

Figure A.23 – Scenario B - South. Parametric analysis of overhang length and roof U-Value (uncomfortable hours).

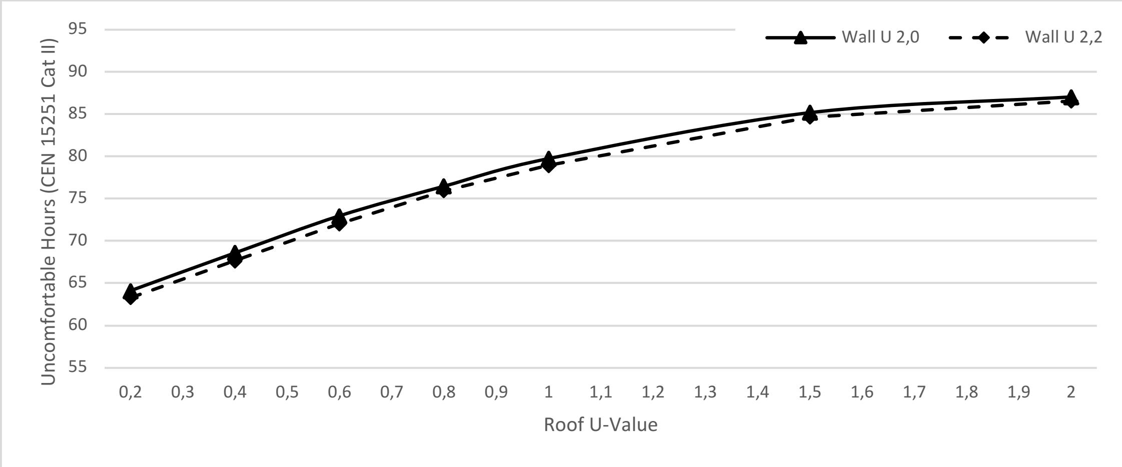

Figure A.24 – Scenario B - East. Parametric analysis of roof and wall U-Value (uncomfortable hours).

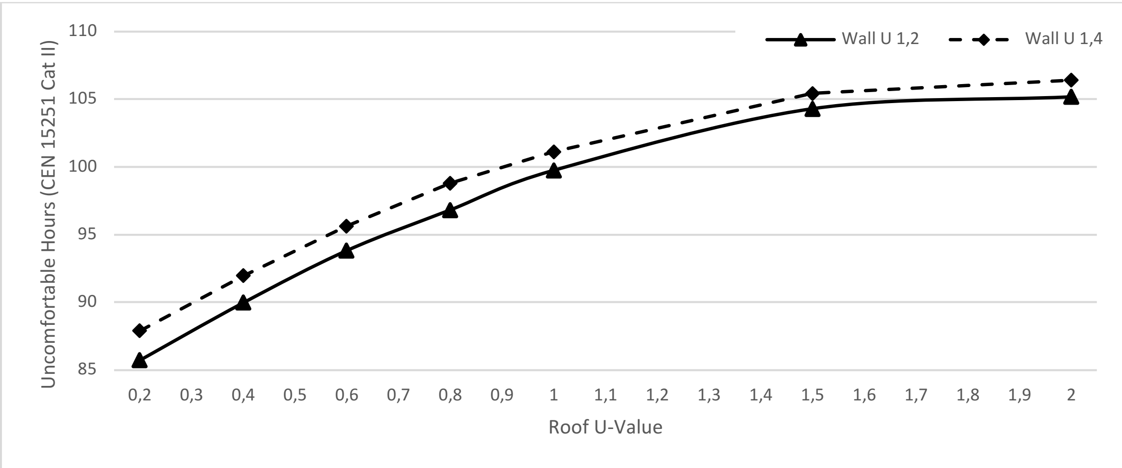

Figure A.25 – Scenario B - West. Parametric analysis of roof and wall U-Value (uncomfortable hours).

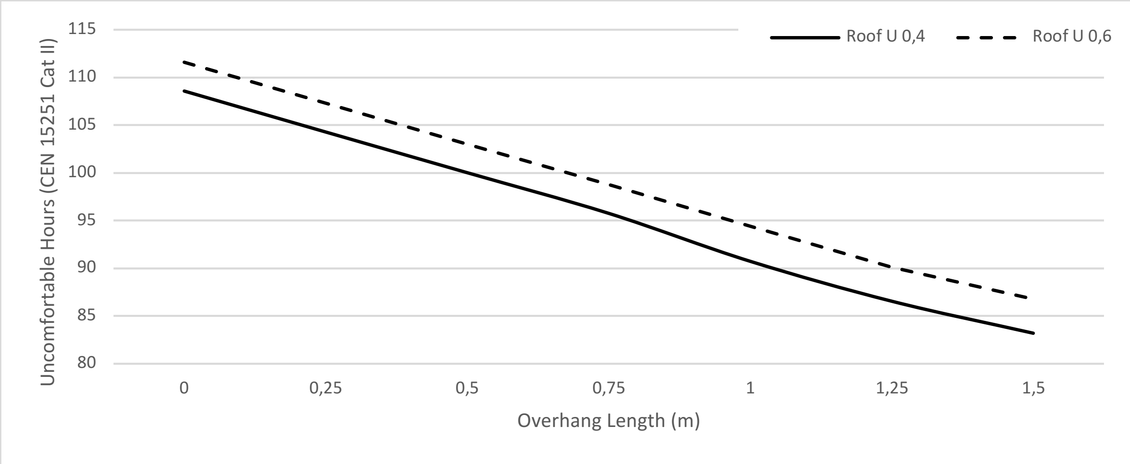

Figure A.26 – Scenario B - West. Parametric analysis of overhang length and roof U-Value (uncomfortable hours).

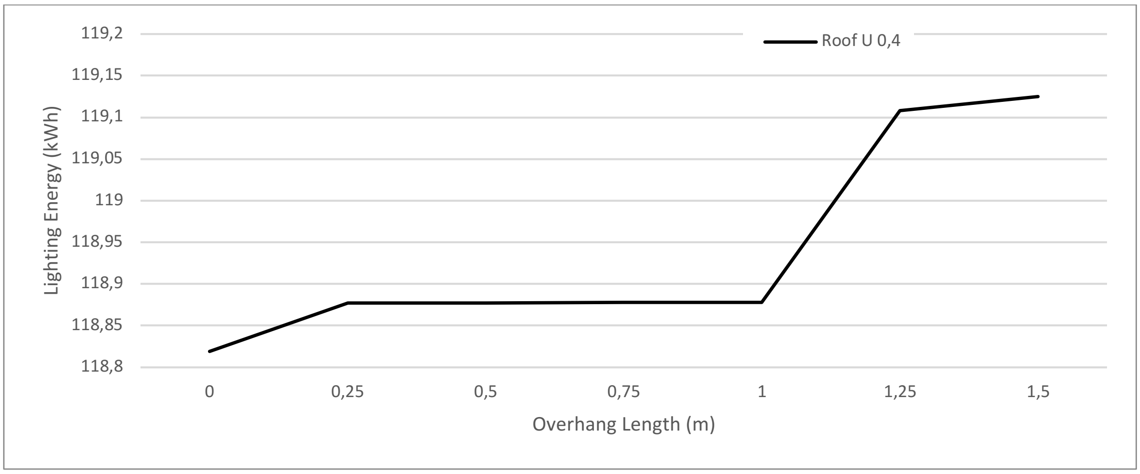

Figure A.27 – Scenario B - West. Parametric analysis of overhang and roof (lighting energy).

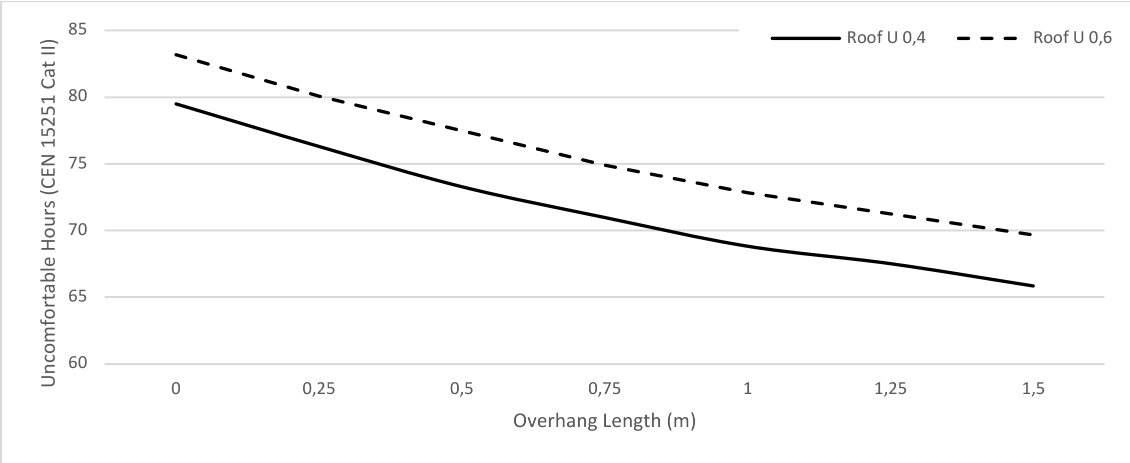

Figure A.28 – Scenario B - East. Parametric analysis of overhang length and roof U-Value (uncomfortable hours).

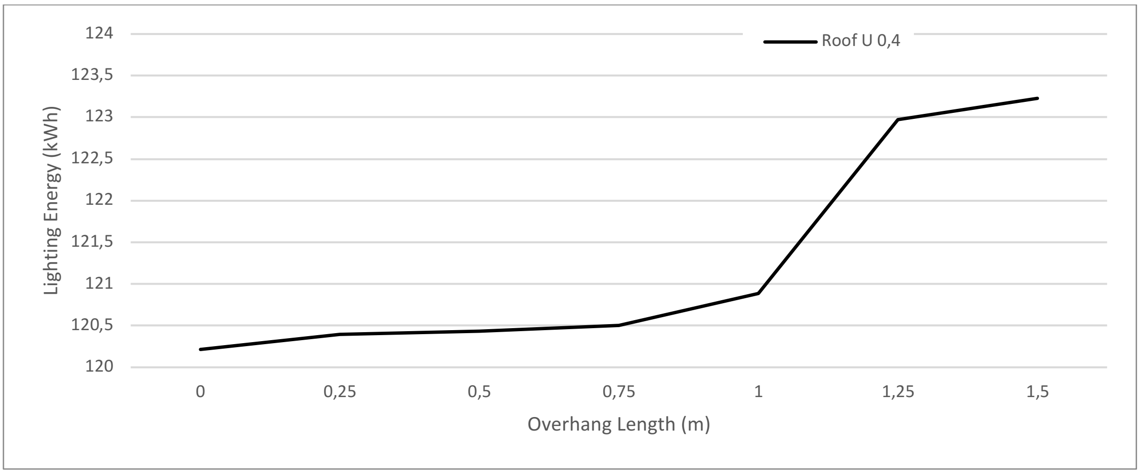

Figure A.29 – Scenario B - East. Parametric analysis of overhang and roof (lighting energy).

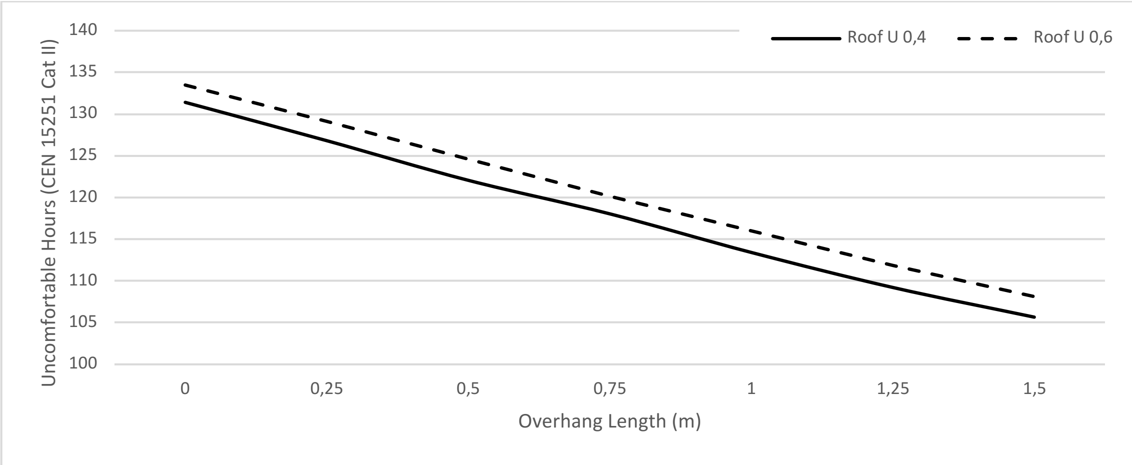

Figure A.30 – Scenario C – West. Parametric analysis of overhang and roof (uncomfortable hours).

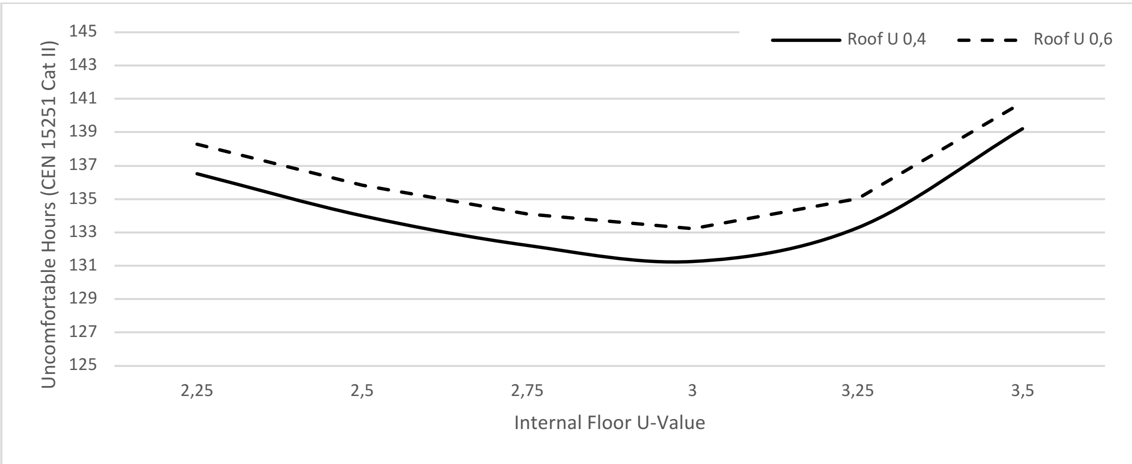

Figure A.31 – Scenario C – West. Parametric analysis of internal floor and roof (uncomfortable hours).

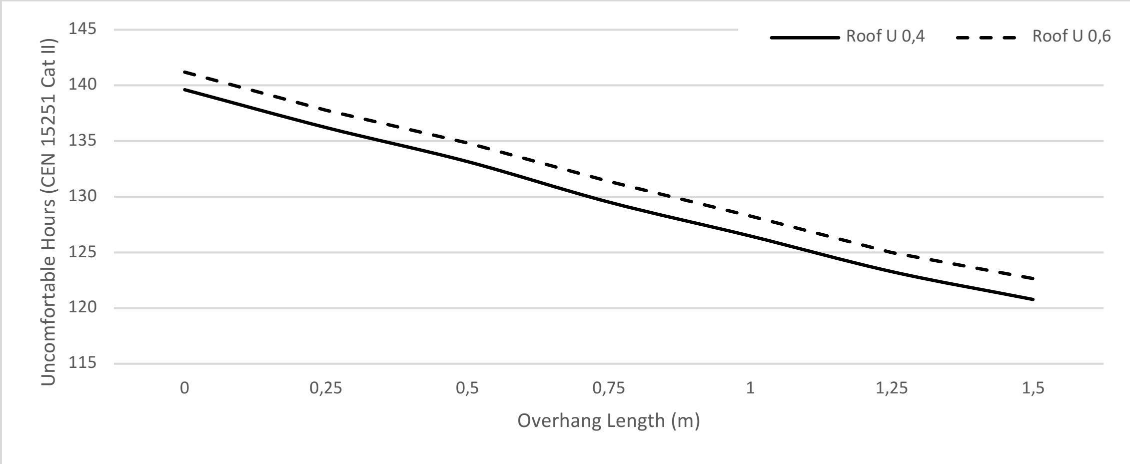

Figure A.32 – Scenario D – West. Parametric analysis of overhang and roof (uncomfortable hours).

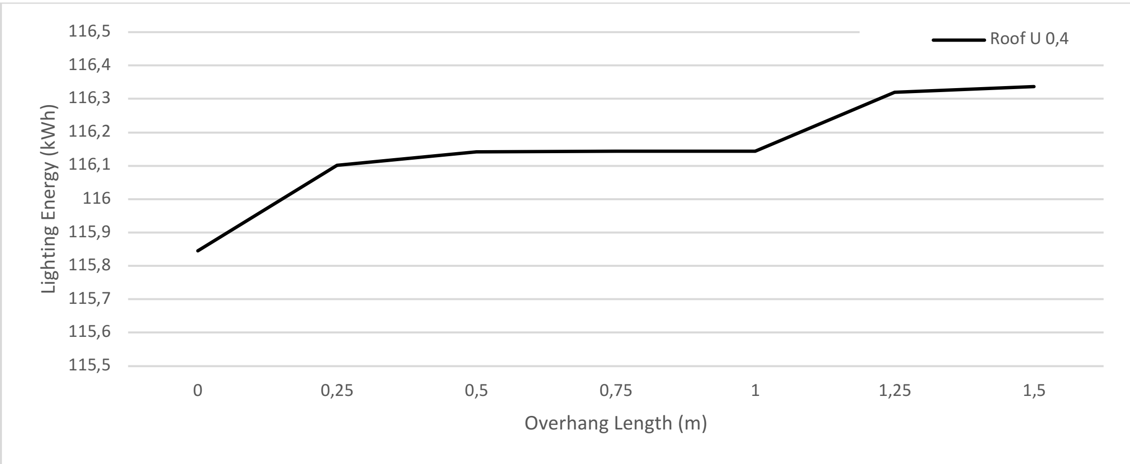

Figure A.33 – Scenario D – West. Parametric analysis of overhang and roof (lighting energy).