University of Pecs, Faculty of Engineering and Information Technology,
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Ph.D. Thesis

A Systematic Approach of Energy Efficiency and Thermal Comfort Strategies for a Prototype of Residential Building Design Using Energy Simulation Tool

Submitted to the in fulfillment of the requirements for the degree of **Doctor of Philosophy in Architecture Engineering**

By

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This Work Is Gratefully Dedicated To The Soul Of my lovely mother who gave me life.

And to my wonderful husband, kids, sisters, and brothers.

you are my fans, you are my life, from all of my heart, May Allah blesses you all.

Sara

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APPROVAL SHEET

This dissertation proposal entitled A Systematic Approach of Energy Efficiency and Thermal Comfort Strategies for a Prototype of Residential Building Design Using Energy Simulation Tool submitted by Sara Mohammed Reda Ali Elsayed Elhadad for the degree DOCTOR OF PHILOSOPHY has been examined and approved for PROPOSAL HEARING.

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ABSTRACT

Buildings are attributed to a tremendous amount of energy consumption due to their continuous operation and extensive lifetime. Rising energy costs and use, particularly in buildings, have prompted academics to examine novel methods and tactics for lowering energy consumption. Beside energy issues, thermal comfort is an important factor in determining the quality of interior spaces. The heat from electrical lights, a lack of proper ventilation, excessive humidity levels, and poorly functioning building envelopes can all contribute to occupational health concerns. Creating optimal thermal conditions to meet human desires for thermal comfort has been identified as a fundamental requirement of the indoor environment. Undesirable thermal conditions can cause occupant dissatisfaction, which has negative impacts on their performance, productivity and even health state. As a result, thermal comfort issues in buildings must be addressed seriously and expeditiously when they arise. The specification of a building's indoor thermal comfort requirements is a necessity for its design, and hence dependable explicit techniques for assessing its long-term comfort performances are required.

Growing energy costs and environmental highlight the significance of sustainable development and energy conservation. Outdoor circumstances, particularly climatic parameters, can have a significant impact on indoor thermal conditions via building envelopes. The passive design adapts to local climate and site circumstances to maximize building occupants' comfort and health while minimizing energy usage. A real-world building from New Minia, Egypt was chosen, and five passive design strategies were investigated using IDA-Indoor and Climate Energy (IDA-ICE 4.8) simulation tool, including thermal insulation, glazing pane, infiltration, fixed shading, and orientation. The results showed that thermal insulation contributed to the most effective passive strategies while infiltration is accounted for the least effective passive strategy. The acceptable thermal comfort hours in all scenarios achieved satisfactory results and the average daily hours for the unacceptable thermal comfort is around 4hours for the whole year. The orientation of the structure is one of the most significant components in passive design since good orientation can increase the passive design features of the building. It

aids in the passive cooling and heating of the structure and makes use of natural light. The optimal building orientation can save up to 6.7% in cooling and 5.8% of total energy demand compared with the existing investigated orientation. The location of the actual building has a noticeable effect on energy consumption.

Performing Building-energy simulations is an essential part of a decision-making process as it helps designers to assess the energy and comfort effect of different building design options. Since the impacts of building physics simulation model simplifications on the accuracy of the results are not well studied and reported, the proposed simplification scenarios seek to overcome the obstacle of long calculation time and according design costs by providing a simpler and faster way to carry out building-energy and comfort simulations. The main aspect of the methodology is to achieve an adequate level of accuracy that can promote the simulation results of energy demand and thermal comfort analysis by simultaneously minimizing calculation time. The detailed reference building physics simulation model contained all separate rooms modeled as individual thermal zones. A detailed model is simplified through four scenarios, by incrementally reducing the number of thermal zones from modeling every space as a separate zone to modeling the building as a single zone. The results indicate that all simplification scenarios present a marginal average deviation in total energy demand and thermal comfort by less than 20%. Combining rooms with similar thermal features into a zone presents the optimal scenario, while the worst scenario is the single-zone model.

Sensitivity analysis is typically performed in conjunction with energy simulations to better understand building performance and minimize consumption. This study investigates the most influential envelope design parameters on the thermal performance of a typical residential building. Sensitivity analysis is used in conjunction with the IDA-ICE 4.8 simulation tool to assess the effects of 33 envelope design parameters for energy consumption and carbon dioxide concentrations. The input parameters include thickness, materials, density, specific heat and thermal conductivity of the basement, exterior floor, interior floor, exterior wall, interior wall, roof, ground slab, glazing type, and infiltration rate. The results show that exterior floor materials have the biggest impact on annual delivered energy for heating and cooling, whereas the thickness of the basement, exterior floors, interior floors, and walls have minimal effects on energy consumption. It is also shown that the impact of all investigated parameters is not sensitive to the carbon dioxide concentration in the building.

Employing more passive solutions can considerably improve building thermal comfort even in extreme weather situations. The findings will be useful in the creation of passive house standards, as well as in future optimization work to achieve both energy efficiency and favorable built environments in residential buildings. The simplification approach is well applicable in further early-stage design and development tasks, specifically in large-scale projects. The sensitivity analysis results assist designers to assess the performance of existing buildings and more efficiently generating alternative solutions in the energetic retrofitting of existing and energy design of new residential buildings.

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Journal Papers

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CHAPTER One

1. INTRODUCTION

1.1 General

High consumption of energy is unavoidable at a global scale (International Energy Agency (IEA), 2012; Malko, 2015; Pérez-Lombard et al., 2008; Solangi et al., 2011; Wolfram et al., 2012). It measures the economic success of a given country. The operation of residential and commercial buildings attributes one-third of the world's energy consumption (Ürge-Vorsatz et al., 2012). Thus, there is great potential for decreasing global energy consumption through improving the building design (Urban and Glicksman, 2006). All advanced countries concerned on building-energy problems in various ways to preserve the energy sources and to use energy in a rational way (Elhadad et al., 2019c). Based on the U.S. Department of Energy report, buildings are attributed to the majority of total annual energy consumptions and greenhouse gas emissions by the range of 40% to 50% (Chen, 2009; Elhadad et al., 2019d), and similar results are shown in Europe (Economidou, 2011). Thus, different supranational and national initiatives, regulations, and different programs of private sectors such as CASBEE, LEED, BEEAM, DGNB, and others identify the parameters and standards to assess buildings' sustainability level and to minimize energy use. The role of appliances and residents' behaviors of users should be taken into account in sustainable building design as this role is strictly connected to energy savings and indoor comfort (Elhadad et al., 2019a; Roberti et al., 2015). Becherini et al. (2018)suggested and modeled several scenarios through which occupant behavior and thermal coating can contribute to the thermal performance of the building. Proper implementation of the framework, materials, knowledge, and system from the design stage to construction and operation stages is required to obtain efficient buildings. The "Integrated Building Design" approach (Picco and Marengo, 2015) is one of the possible solutions to integrate all these elements in the building sector.

The upward trend in construction consumption is projected to continue in the next years (Yan et al., 2015). Human occupants have an important role in the relationship between building energy usage and indoor environmental quality (IEQ). They also release pollutants such as carbon dioxide (CO_2), which is a sign of adequate ventilation. Indoor loads are impacted by human occupant behavior such as window operation, lighting, blind and fan operation, temperature adjustments, and the usage of receptacle appliances, which in turn affect building energy consumption (Yan et al., 2015). Human occupant behavior modeling and energy consumption research has been conducted in a variety of building systems such as ventilation, air conditioning, and lighting. Daylighting parallel with sun protection is an essential factor in architecture and a sustainable method in the construction of energy-efficient buildings (Ihm et al., 2009). It has recently become an important aspect of ecologically responsible building design (Kim et al., 2012). it is possible to significantly reduce electric energy consumption through architectural projects that maximize the use of natural illumination level (Doulos et al., 2008; Kim et al., 2012; Lee and Selkowitz, 2006; Li et al., 2006; Singh and Garg, 2010; Tíba and Leal, 2012). In summary, occupants and their behavior have a considerable impact on building IEQ and energy consumption and are a major source of uncertainty in predicting building energy usage (Yan et al., 2015).

Several design techniques, such as passive and active design solutions, could be regarded among building energy efficiency approaches. active techniques emphasize the use of energy-efficient building service systems such as heating, ventilation, air conditioning (HVAC), lighting, and hot water systems (Chen et al., 2015). Instead of mechanical systems, passive design is any technology or strategy that increase energy-efficiency and thermal comfort by taking advantage of the climate, the interior environment conditions to minimize energy demand by utilizing energy-efficient building design features such as the shape, layout, and building envelope (Yu et al., 2020). In many hot and arid climates, passive design solutions have been recommended as an effective way to produce optimal interior climatic conditions in residential buildings and thereby minimize energy usage. Furthermore, it minimizes greenhouse gas emissions, which extends the life of a building and our planet (Ahsan, 2009).

Accurate energy analysis takes time, up to several weeks in more complicated cases, and the more accurate the analysis must be, the more time it will need. This contrasts with the need to minimize the time requirements of the analysis so that it can be consistent with design timelines but doing so necessitates simplifications of the building model and a simulation approach, with the disadvantage of a loss in accuracy. In this context, it is crucial to establish a methodology for introducing simplifications to the building simulation model that do not degrade the quality of simulation results while also allowing for the reduction of time and costs associated with building energy simulations.

In building science, designers and researchers frequently use dynamic thermal simulation software to analyze the energy and thermal performance of buildings to achieve specific goals, such as lower energy consumption, improved indoor thermal comfort, or reduced environmental effects (Elhadad et al., 2019d; Garber, 2009; Katona et al., 2020). As a result, several techniques for supporting building simulation analysis have been developed, such as simulation-based optimization, parametric simulations, sensitivity analysis, meta-model analysis, etc. Numerical simulations are frequently used to assess the energy performance of buildings. Despite many recent developments in software to simulate building energy requirements, the discrepancy between predicted and actual energy consumption remains a constant issue. One reason behind this disparity in existing buildings may be due to uncertainties in the thermal and physical properties of building materials (Hughes et al., 2015). Uncertainty and sensitivity analysis is an effective tool to identify uncertainties in a system's or simulation tool’s input and output (Fuerbringer, 1994; Lomas and Eppel, 1992; Macdonald, 2002). The importance of sensitivity analysis in building energy analysis cannot be overstated.

1.2 Problem Statement

In the context of global warming and decreasing natural energy resources, it is crucial to focus on lowering energy consumption in buildings. A growing interest in improving energy efficiency in buildings has resulted in progressive legislation, emphasizing the need to expand understanding of building energy performance and driving research activity in this field. Several factors have contributed to the inefficient building stock, including a construction boom; a lack of strong green building standards and norms; artificially low power rates; and little awareness of green building techniques (Aswad et al., 2013). As a result, there is a contribution of temperature discomfort inside the indoor areas, therefore thermally uncomfortable most of the time. To mitigate the effects of this exposure, residential buildings have resorted to the use of elaborate HVAC systems, which have drawbacks such as high energy consumption and increased CO_2 emissions into the environment. Thus, passive design strategies that are well-designed preserve the optimal environment for human habitation while decreasing energy costs. The passive design integrates a wide range of climate-based strategies to increase occupant thermal comfort and minimize the need for mechanical systems for heating and cooling (Rana, 2021). It is clear from the above that passive building design is critical for a variety of reasons.

Building-energy simulation is an essential support tool to design and commission green buildings. Many available, validated building-energy simulation tools, such as Energy Plus, IDA ICE, TRNSYS, BLAST, ESP-r, Radiance, DOE-2, and eQUEST promise high accuracy level and effectivity for a comprehensive simulation of building designs (Elhadad et al., 2018; Picco et al., 2014), but they require detailed input for model analysis, composing of zero thickness partitions or walls between thermal zones (Chatzivasileiadi et al., 2018). The operation and input of building-energy simulation parameters are quite complex (Fonseca i Casas et al., 2018), including geometric modeling, division of thermal zones, software selection, and selection of meteorological data. Geometric modeling represents the first stage of simulation and often consumes about half of the time of the simulation procedure (Zhao et al., 2018). Thus, simplification of geometric modeling is one of the most crucial ways to enhance the simulation process. Converting a detailed model back to the spatial model is a complex task for the user and represents some of the unfortunate challenges (Chatzivasileiadi et al., 2018). When creating a simulation model of a building, it is important to examine how exact and detailed the model of the real building should be, as well as what differences will result from particular simplifications that are used. Adopting a more detailed model requires a significant rise in the time necessary for development and simulation, resulting in significantly higher costs.

Efficient design is crucial, especially early stage on, because poor decisions made early on are difficult or impossible to fix. Existing energy modeling tools, due to their excessive complexity and necessary technical expertise, fail to fulfill the demands of architects and building designers during the early phases of design. The suggested simplification technique aims to satisfy this demand by offering a quick and easy way to do building energy simulations and aid in the selection of appropriate building components and systems during the early design stages. The methodology's most important component is obtaining an appropriate and known degree of accuracy that can verify the simulation findings and offer reliable and valid information on the thermal behavior of the various solutions evaluated by the design staff.

Despite recent developments in building energy simulation tools, the gap between actual and predicted energy consumption remains a challenging issue. This disparity may occur in existing structures due to uncertainty in the thermophysical characteristics of building materials (Hughes et al., 2015). As a result, estimating real material characteristics improves the accuracy and reliability of building simulation software. It is critical to have models that analyze the influence of variable input parameters on physical phenomenon predictions. By focusing on the most influential parameters, the number of parameters to be estimated via in-situ measurement may be decreased. The use of sensitivity analysis is an appealing method for highlighting the key parameters and their influence on the interesting model outcomes.

1.3 Motivation and Objectives

The growing concern about the environmental effect of buildings and the quality of their indoor environments has sparked a discussion regarding the role architects should play in building environmental design. Passive design strategies are extremely important and should not be underestimated since it is a practical option for providing comfort to people living in buildings while significantly lowering their energy (electricity/gas) expenses. This study will also help to increase awareness about energy efficiency in buildings, which is achieved by using passive design strategies to reduce the effects of harsh climatic conditions. In addition improving the thermal comfort of the users within the building, it also aims to identify certain passive design issues such as; the appropriate orientation for residential buildings in the city of New Minia, and the suitable insulation materials to be used in the building fabric, fixed shading, glazing and infiltration rates for providing energy efficiency. Accurate energy and thermal comfort analysis of buildings require a lot of time, especially in complex cases it may require up to several weeks. Minimizing the required time of analysis is necessary to be compatible with design duration. A better knowledge of which energy modeling input parameters have the most influence on energy modeling accuracy will assist industry members in making educated judgments when assessing upgrade alternatives baseline performance evaluation and sensitivity analysis conducted, contribute to the knowledge on the performance of residential buildings envelope components and their sensitivities. Most studies focused only on one or two aspects of modeling and assessing the building's thermal performance where a systematic approach is required:

- To evaluate the utility of using selected passive cooling solutions to reduce the climatic effects, improve thermal performance to the occupants and minimize energy consumption in residential buildings.
- To analyze and quantify the importance of building orientation on its energy consumption.
- To assess the impact of model simplifications through different scenarios considering the simulation time, modeling time, and accuracy level of the derived results in both energy demand and thermal comfort in a residential house.
- To identify the most important envelope design parameters for buildings.

The Specific objectives are:

- To know the state of the art in building information modeling applications, including introducing and using one of the most essential (IDA ICE) for the design and energy simulation of the study building.

- To improve the quality of life for low-income families in affordable housing complexes by analyzing and offering solutions that increase energy efficiency and thermal comfort.
- To investigate the passive design strategies that correspond with the climatic region to enhance the thermal comfort of buildings and to decrease the energy consumption.
- To determine if the influence of building orientation on energy consumption is affected by the location of the building, particularly when the latitude varies.
- To explore what level of simplified thermal zoning is required to support energy and thermal comfort analysis of residential buildings
- To quantify the impact of simplification scenarios on the energy use, thermal comfort, and daylighting of residential buildings.
- To identify the optimal scenario of the proposed simplification scenarios.
- To perform sensitivity analysis of 33 envelope design parameters for energy consumption and carbon concentrations.
- To identify various issues of sensitivity analysis documented in prior studies.
- To find important parameters through Sensitivity analysis in conjunction with IDA-ICE 4.83.
- To generate alternative design solutions in the design of new and retrofitting residential buildings.

One of the objectives of this thesis is to support the Government in their decision making by providing access to improved (processed) data and to provide planners with tools to assess the utility of using selected passive cooling solutions to reduce the climatic effects, improve thermal performance to the occupants and minimize energy consumption in residential buildings in hot desert climatic situations and explore important parameters through the sensitivity analysis. One of the challenges for the study is to feed their knowledge into regional and national planning systems to manage the thermal energy performance of residential buildings in a hot and arid climate now and in the future.

1.4 Research Question

- What are the potential effects of different passive design strategies on the thermal performance of the building in a hot and dry climate?
- What is the best set of passive design strategies that can be proper with the climatic region to enhance the thermal comfort of residential buildings?
- What is the impact of building orientation on energy consumption?
- What is the effect of the building's location on the building’s thermal performance?
- what level of simplified thermal zoning is required to support energy and thermal comfort analysis of residential buildings?
- What are the most important envelope design parameters for buildings?
- How can sensitivity analysis be applied to improve the performance of energy simulation for the existing building?

Specific questions

- How can the passive design strategies for residential buildings improve thermal comfort to the occupants and reduce energy consumption?
- What is the optimal orientation of the dwelling object of study?
- What is the effect of the building's location on the building's thermal performance?
- What is the impact of model simplifications on energy demand, thermal comfort, and visual comfort in residential houses?
- How can sensitivity analysis be applied to assist designers to generate alternative solutions in the energetic retrofitting of existing and energy design of new buildings?
- How can sensitivity analysis assist designers in the early stages of envelope design for newly constructed buildings, as well as envelope rehabilitation of existing buildings?

To achieve the study’s aims, the research strategy has been designed as follows:

- The study first searched for useful and common and passive design strategies in a similar climate via a literature review. Then, five strategies were selected for a typical residential building in hot and dry climates, a case study of New Minia, Egypt. The study employs IDA-Indoor and Climate Energy (IDA-ICE 4.8) simulation tool. The energy-saving of passive design techniques is based on the comparison of annual reduction in energy consumption. Thermal comfort and visual comfort were assessed by computing carbon dioxide concentrations and daylight for each passive strategy. Eight orientations are assessed: south, south-east (base case), east, north-east, north, north-west, west, and south-west. The analysis of the simulation results is based on the comparison of heating and cooling loads of different orientations. To meet all of the objectives, the location will be shifted from New Minia to Cairo, Alexandria, and Aswan.
- For the purpose of the model simplifications, a multifamily house in a hot and arid climate as a reference is proposed, representing a generic, typical residential building type in the largest building sector of the world. Four different simplification scenarios of the thermal zones are proposed. First, in the base scenario model, each space is modeled as a single independent zone. Then, scenario S1 combines spaces with similar characteristics (e.g., orientation, operation schedules, same use, etc.) into one thermal zone. Then, scenario S2 combines the same oriented spaces for all of the 4 floors into one thermal zone. In scenario S3, all spaces on the same floor are merged into one single zone, and scenario S4 models the entire building as one single thermal zone. IDA ICE has been used to simulate thermal and visual comfort as well as energy performance in a detailed model about the reference building and several simplification scenarios. The differences of total energy and comfort performance in the detailed and simplified models are analyzed to evaluate the grade of the simplifications' accuracy.
- A two-storied residential building was used as a case study to demonstrate the use of the proposed methodology in practice sensitivity analysis in conjunction with the IDA-ICE 4.8 simulation tool to identify the most

important envelope design parameters. 33 envelope design parameters for energy consumption and carbon concentrations were considered. The input parameters included the thickness, materials, density, specific heat, and thermal conductivity of the basement, exterior floor, interior floor, exterior wall, interior wall, roof, and ground slab, glazing type, and infiltration rate. Assign the baseline design parameters and compute the output of the baseline case. Output distribution is computed due to the variations of a given input parameter, and the sensitivity coefficient is determined for each case. Finally, the impact and significance are evaluated of each design parameter on the output variables

1.5 Structure of the Thesis

This thesis consists of seven chapters including the introduction in Chapter 1 and conclusions in Chapter 7.

Chapter (1) Introduction: Includes problem statement, research objectives, and scope of the thesis.

Chapter (2) Literature Review: presents a review of literature on passive design strategies, thermal comfort, visual comfort, and simplifications of the building model and a simulation approach, techniques for supporting building simulation analysis, uncertainty, and sensitivity analysis.

Chapter (3) Passive Design Strategies for Residential Buildings: evaluate the utility of using selected passive design strategies to improve thermal performance and minimize energy consumption in residential buildings in hot desert climatic situations, namely New Minia, Egypt. A real-world building was chosen for this study, and five passive solutions were investigated.

Chapter (4) The Impact of Building Orientation on Energy Performance: quantify and analyze the effect of building orientation on its energy consumption for a residential building located in a hot and arid climate, a case study of New Mina, Egypt. The location of the building is changed to Cairo, Alexandria, and Aswan to investigate the impact of location on the building energy performance, especially when the latitude is different.

Chapter (5) Model Simplification on Energy and Comfort Simulation Analysis for Residential Building Design in Hot and Arid Climate: investigates the impact of model simplifications through different scenarios considering the simulation time, modeling time, and accuracy level of the derived results in both energy demand and thermal comfort in residential houses. The study is carried out in the simulation framework of IDA ICE, and it also identifies the optimal scenario of the proposed simplification scenarios.

Chapter (6) A Sensitivity Analysis for Thermal Performance of Building Envelope Design Parameters: identifies the most important envelope design parameters for buildings in general, but a two-storied residential building was used as a case study to demonstrate the use of the proposed methodology in practice. Sensitivity analysis of 33 envelope design parameters for energy consumption and carbon concentrations was performed.

Chapter (7) Conclusions and Recommendations for future studies

References: Have been shown at the end of the chapters.

Appendices: Appendix (A&B) contains the data entry and computer programs.

CHAPTER Two

2. LITERATURE REVIEW

Computer models play an essential role in integrated building design providing a range of support to the thermal performance of building and decision making. Passive design strategies offer potential and cost-effective approaches for lowering building energy consumption. This chapter offers a review of passive design strategies, thermal comfort, visual comfort, and simplifications of the building model and a simulation approach. Moreover, techniques for supporting building simulation analysis, uncertainty, and sensitivity analysis are presented.

2.1 Energy-Efficient Design Strategies

Energy efficiency may be accomplished by incorporating passive or active strategies into building design to reduce cooling, ventilation, heating, and lighting loads based on climatic demands and circumstances. Active solutions primarily rely on the use of energy-efficient building service systems to decrease energy waste during the building operation stage (Chang et al., 2018; Ma et al., 2016). The passive techniques, on the other hand, harness the indoor environment conditions by utilizing building design elements like layout and shape rather than mechanical systems. Passive energy-saving solutions enhance the utilization of natural resources such as heating, cooling, ventilation, and lighting to provide a comfortable building environment with a low energy demand (Gou et al., 2018; Omrany and Marsono, 2016). When compared to active solutions, passive designs often have lower life cycle costs (Singh et al., 2016), more substantial energy-saving effects (Dahlstrøm et al., 2012), and longer lifespans Energy efficiency will be attained if a building is completely developed using passive design concepts and tactics. This is because passive design aims to reduce energy consumption in buildings while still providing comfort to building inhabitants. The United Nations defined energy-efficient buildings as those with the fewest energy inputs in 1991.

2.1.1 Passive design strategies

Passive design, often known as 'bio-climatic design,' aids in the maximization of occupant comfort and health by integrating local climatic and site factors with architectural design and building technology (Yao, 2006). The notion of passive design, as highlighted by Olgyay (2015) and Givoni (1976), is to heat, cool, and light buildings utilizing innovative design approaches and materials while decreasing or even eliminating the need of any energy system. Passive design is a phrase that refers to a wide range of techniques or tactics aimed at achieving energy-efficient building design and better occupant comfort. As a result, passive design and energy efficiency are inextricably linked. Passive design is defined as any strategy or technology that increases energy efficiency and thermal comfort by taking advantage of the climate, without the need for expensive mechanical systems (Fernandez, 2017). Passive design for any building includes infrastructure, architecture, and devices that achieve a result by directly using natural forces/ambient energy without conversion, such as passive/free ventilation, night cooling, shading technology, daylighting, and building envelope adjustments such as changing window to wall ratio (WWR), building orientation, glazing, and green roofs to reduce the energy demand for heating, cooling, ventilation, and lighting. The goal of passive strategies is to maximize the utilization of natural resources while also adjusting building design. For example, daylighting optimization can assist to lower the energy demand for artificial lighting, which accounts for 14% of total electrical consumption in the European Union and 19% globally (Zissis, 2016). It can also be used with shade devices to minimize energy consumption.

Passive cooling makes use of free, renewable energy sources such as the sun and wind to provide cooling, ventilation, and lighting for a home. This also eliminates the requirement for mechanical cooling. Passive cooling implies lowering temperature differences between outside and inside temperatures, increasing indoor air quality, and making the building a better and more comfortable place to live or work. It can also reduce energy consumption and environmental implications such as greenhouse gas emissions. Several passive cooling solutions might be advised for usage in hot, dry climates such as those found in Egypt. Proper window placement and daylight design, the selection of suitable glazing for windows or skylights, proper shading size of glass when heat gains are avoided, the use of light or reflective-colored materials for the building envelope and roof, careful siting and wise orientation decisions, and appropriate landscaping design are all design strategies that reduce the need for mechanical cooling systems (Asimakopoulos and Santamouris, 1996). The use of passive design solutions in modern buildings attempts to remove the need for mechanical cooling equipment or to minimize the size and expense of equipment, hence lowering maintenance operations (Yao et al., 2018). Many different forms of passive cooling solutions might be employed in hot places to provide a better, healthier, and more efficient building environment. These solutions are mostly used for openings (windows transparent building envelopes), increasing thermal mass (roofs and walls), reducing incident solar radiation, and enhancing air quality. As a result, the building's heat responsiveness and energy performance will be enhanced. Ahsan et al. (2019).used passive cooling techniques to minimize operational energy usage in Pakistan. The results showed that passive cooling solutions saved 35% of the energy.

Despite the limited overview of these approaches, the material offered in this study is thought to provide a clear picture of what and how passive strategies might be employed to improve building performance in hot locations. Several studies focused on passive design strategies in a location with a mild temperature, a dry winter, and a hot summer reveal possible energy savings while maintaining adequate occupant comfort (Attia et al., 2012; Chen et al., 2018; Gupta and Tiwari, 2016). The most often used passive design technologies are divided into four categories: (1) geometry, (2) passive envelope, (3) solar shading, and (4) natural ventilation. The geometry of a structure influences its self-shading, daylight availability, solar gain, natural ventilation, noise management, and pollution dissipation (Chen et al., 2015). A modest degree of self-shading can enhance total energy performance in residential structures since the decrease in cooling load overcomes the minor increase in lighting energy (Gupta and Tiwari, 2016).

2.1.1.1 Geometry

Geometry influences the availability of natural ventilation within the building, particularly wind-driven ventilation. Wind availability may be maximized by carefully selecting building orientation and location. Comparisons of simulation findings across various public residential buildings in Hong Kong indicate unequivocally that some types of layout (e.g., Concord type) have fewer hours of discomfort in Hong Kong, even under free-running conditions (Kwok et al., 2017). Furthermore, passive design in geometry and layout includes the early stages of design and so typically does not necessitate any additional cost. Oral and Yilmaz (2003, 2002) provided an approach for determining the building shape that delivers the least amount of heat load. Marks (1997) also investigated the optimal proportions of wall lengths, angles, and glazing factors for multistory office structures in Australia. Jedrzejuk and Marks (2002) expanded on the research by presenting a multi-criteria optimization approach for building design and structure, as well as heat source optimization. The qualities of building envelopes have a considerable impact on the thermal performance of the building (Chen et al., 2015).

2.1.1.2 Building orientation

The orientation of the building refers to the selection of a suitable location based on the basic directions (East, West, North, and South) to provide comfort to users. The appropriate orientation of the structure means that sunlight should not enter the interior areas since it raises the temperature, reducing internal comfort. Furthermore, the structure must be angled according to the sun path, and the apertures for cooling breezes must be located away from the dust-laden wind. Various site concerns might generate design possibilities or limits on the passive design techniques that are applied. To improve the integration of passive cooling solutions, factors such as the orientation of the building on-site, shadow from nearby structures and plants, wind flow patterns, and so on must be considered. This starts with climate study; a simple examination of the local environment offers the architect a sense of how solar heat gain may be limited and natural ventilation can be enhanced, and these two aspects are the primary goals necessary for passive cooling.

A well-oriented home utilizes energy more efficiently, making it less expensive and more comfortable to live in, whereas a poorly oriented house excludes the sun during the winter season and causes the temperature within the structure to rise during the summer season (Reardon et al., 2013). According to Gut and Ackerknecht (1993), the building's long axis should run east-west to allow for the least amount of solar heat gain via the building envelope. Wong and Li (2007) investigated the effectiveness of passive climate management measures such as building orientation in Singaporean residential structures using field measurements and computational energy models. According to their findings, the optimal orientation for a building in Singapore with its tropical environment is for the building's long axis to run east-west. They also suggest that by following this orientation, the cooling load for a residential building may be lowered by 8% to 11%. According to Watson and Labs (1983), a home may be made more energy-efficient if it is designed with sun orientation and prevailing wind direction in mind. They did, however, indicate how much energy may be saved by such preparation. Overheating caused by sun radiation is a major issue in Northern Nigeria, particularly in Bauchi during the dry season throughout the day.

Bichiou and Krarti (2011) performed a study on single-family dwellings in five distinct areas in the United States. The building form, WWR, and orientation were all deemed key elements for optimization in this study. Three optimization techniques were explored, and the best design lowered life-cycle costs by 10–25% depending on the kind of dwelling and climate. Orientation, location on site, modifying the microclimate, and natural ventilation may potentially reduce the energy consumption of a house by 20 percent (Morrissey et al., 2011). According to research conducted in Teheran, building orientation may save up to 10.5 percent of a building's yearly energy, and the WWR plays an essential role in determining building orientation (Fallahtafti and Mahdavinejad, 2015). As a result, in determining the effect of building design on energy usage, it is critical to investigate the impact of orientation on energy efficiency.

2.1.1.3 Building envelope

Heat enters and exits the home via the roof, walls, windows, and floor. Heat dispersion within a home is influenced by internal walls, doors, and room configurations. These components are referred to collectively as the building envelope. The building envelope is a critical component to consider in passive architecture. The exterior envelope of a structure is intended to withstand solar heat gain while also enabling interior heat gains to be evacuated from the building's envelope.

The integrated design of building shape and materials as a comprehensive system to achieve maximum comfort and energy savings is known as envelope design. To optimize thermal performance, a good envelope design adjusts to climate and site variables. It has the potential to reduce operating costs, improve comfort and lifestyle, and reduce environmental impact. Because the major purpose of tropical building design is to reduce direct heat acquisition through radiation through openings and interior surface temperature, the building should be constructed with shielded openings and walls (Gut and Ackerknecht (1993). The exterior walls can be protected by designing the roof to extend far beyond the line of the walls and have wide overhanging eaves. Cheung et al. (2005) did research to minimize cooling energy for high-rise apartments by improving building envelope design. According to their findings, yearly cooling has a nearly linear connection with the solar absorptance (the amount of solar radiation that goes through a material) of the exterior surfaces. Lower solar absorptance resulted in significant energy savings. A 30% reduction in solar absorptance can result in a 12% reduction in annual necessary cooling energy. They determined that choosing white or light-colored exterior wall treatments may save 12 percent on cooling energy.

For passive design strategies, Building envelope systems may play an essential role in energy consumption reduction and thermal comfort for occupants (Abdou et al., 2021). Architectural design elements such as window-to-wall ratios and building forms, as well as thermal properties of building materials, are taken into account For passive design solutions (Abdou et al., 2021). Furthermore, modern or well-designed mechanical systems can provide an opportunity for improved thermal comfort management and energy savings (Suh and Kim, 2019). Sadineni et al.(2011) investigated the potential of passive strategies for improving IEQ as well as thermal and visual comfort. According to the study, the building envelope is an important passive strategy for energy savings, IEQ, and thermal and visual comfort. Okba (2005) identified the building envelope design as an important component in determining how much energy a building consumes throughout its operating phase. Building envelops design may influence 20–60% of building energy intake, making it critical for high-performance, sustainable buildings (International Energy Agency, 2013). The thermal insulating layer is one of the common passive building envelope design strategies. The thermal insulation layer is constructed of materials with poor heat conductivity, such as wool and polystyrene. Thermal insulation decreases energy input from the envelope by lowering the U-value of the exterior wall. In an experiment, Zhang et al. (2017) discovered that the highest insulation efficiency occurs when the innermost layer on the exterior wall reduces the heat transfer rate by 35–86 percent. The ideal thickness for insulation varies greatly based on the building location and materials (Adamczyk and Dylewski, 2017). According to Wu and Skye's study, energy efficiency measures from passive design solutions are prioritized (Wu and Skye, 2021).

2.1.1.4 Window-to-Wall Aspect Ratio

Windows have the greatest U-value of any envelope element. As a result, if daylighting control is used, the WWR and window total area have a significant impact on the heating and cooling demand, as well as the energy demand for lighting. Aside from that, windows are required for additional passive measures such as unrestricted ventilation. Alwetaishi (2019) studied the influence of WWR and orientation on energy consumption to find the appropriate WWR for educational buildings in various climatic zones, and a WWR of 10% is suggested for a hot and humid climate region. Mangkuto et al. (2016) conducted simulation research for buildings in tropical climates to explore the influence of WWR, window orientation, and wall reflectance on lighting energy consumption and daylight metrics. The optimum design, as determined by Pareto optimization, has a WWR of 30%, a wall reflectance of 0.8, and a south orientation.

2.1.1.5 Shading

Shading of a building envelope may lower temperatures, increase comfort, and save energy. The most basic technique for controlling solar heat gain in building interiors is to include shading devices into the building exterior. Sun shading devices can be either internal or exterior, and it is critical to limit or remove solar radiation from entering the structure. The installation of extra fixed shade systems/overhangs, as well as interior controlled shading, is the third examined passive technique (only for the Italian case). Shading is essential to minimize excessive heat gains in the summer and, as a result, decrease cooling energy demand, which is particularly important in the Mediterranean and non-residential buildings with large window areas. In the winter, the additional window space boosts solar gains and so decreases heating demand. However, increasing summer temperatures boost cooling demand. As a result, shading solutions that allow for large gains in the winter and modest gains in the summer are required. Horizontal devices, vertical devices, and egg-crate devices are examples of shading devices. Hachem et al. (2011) proved that the number of shading facades and the shading to shaded facade ratio had a considerable effect on solar radiation on non-convex structures.

2.1.1.6 Natural ventilation

With the severe heat that builds up by midday, living in a hot area may rapidly become uncomfortable for its people. As a result, the building structure must have good ventilation and an inside temperature that is lower than the external temperature. Natural ventilation keeps the air circulating throughout the indoor space, keeping the resident's cooler even when no energy is used. When used correctly in building design, natural ventilation may improve occupant interior comfort levels and conditions while reducing energy usage in mechanically ventilated (air-conditioned) buildings. Natural ventilation can help to reduce indoor air pollutant concentrations by enhancing a building's indoor air quality. Natural ventilation may be accomplished in two ways: regulated (through apertures such as windows) or uncontrolled (through unintentional openings such as gaps around windows). Wong and Huang (2004) conducted comparative research on the indoor air quality of naturally ventilated and air-conditioned bedrooms in Singapore residential complexes. They discovered that the CO_2 levels in bedrooms that use air conditioners are consistently higher than those that use natural ventilation.

When the thermal comfort of air-conditioned bedrooms and naturally ventilated bedrooms is compared, the air-conditioned bedrooms are frequently significantly overcooled, resulting in exceptionally high PPD (Predicted Percentage Dissatisfied). In naturally ventilated bedrooms, however, the use of fans was adequate to attain the desired thermal comfort. They also discovered that residents who used air conditioners had greater SBS (sick building syndrome) symptoms than those who used natural ventilation. Liping et al. (2007) also conclude that natural ventilation is an appealing alternative for reducing the difficulties associated with air-conditioned buildings since natural ventilation offers potential benefits such as lower operating costs, higher indoor air quality, and sufficient thermal.

2.2 Thermal Comfort

One of the most fundamental requirements of a comfortable environment is to keep thermal conditions suitable for occupants since they have a direct impact on their productivity, health, and morale(Budaiwi, 2007). When a thermal balance is achieved, thermal comfort is obtained (in which no heat storage occurs in the body). Although this is possible in a wide variety of thermal-environment settings, thermal comfort is linked with circumstances that the body can easily adjust to(Budaiwi, 2007). It is defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE, 2004) as " the state of mind that reflects satisfaction with the thermal environment (Ho et al., 2009). A concept on which most people can agree, but one that is difficult to translate into physical characteristics (Budaiwi, 2007). The word mind implies that it is a subjective concept; yet, there has been a substantial study in this field, and a variety of indices exist that may be used to measure locations for thermal comfort (Fanger, 1970; Shek and Chan, 2008). However, Atmaca et al.(2007) proposed three comfort conditions: the body is in heat balance, and the mean skin temperature and perspiration rate are within the range necessary for comfort. A heat balance equation can be used to obtain the conditions necessary for heat balance.

Humans require energy to conduct labor and generate heat in order to maintain a body temperature of roughly 37°C. If the core body temperature drops by more than 1°C, hypothermia develops; if it rises by more than 1°C, a person may suffer from heatstroke (Alder, 1999). The higher the degree of activity, the more heat is created. When the body produces too much heat, it sweats, which causes pain. If there is insufficient heat production, blood is drained from the hands and feet, skin temperature falls, and the individual feels chilly and uncomfortable (Havenith et al., 2002). Furthermore, clothing interferes with our capability to release heat to the environment. The insulating effect of clothes on the wearer is critical to thermal comfort. Clothing insulation is measured in CLO (1 CLO = 0.155 m^2 K/W; the units are those of internal resistance) (Szokolay, 2014).

2.2.1 Thermal comfort design criteria

The primary design criteria for thermal comfort is often air temperature. As a result, it is critical for occupant well-being, productivity, and efficiency (Stein and Reynolds, 2000). Wong and Khoo (2003) determined from their field research in Singapore for classrooms (mechanically ventilated by fans) that the appropriate temperature range is 27.1^{oC} to 29.3^{oC}, meaning that ASHRAE Standard 55 is not entirely applicable in free-running buildings in tropical climates. The neutral temperatures (those at which the majority of participants felt neither too hot nor too cold) for the two types of classrooms were 26.8^{oC} and 27.4^{oC}, respectively. Despite their importance, the findings of this research have yet to be translated into comprehensive and widely recognized standards for tropical naturally ventilated structures (Adebamowo, 2007).

The rate of evaporation from the skin is affected by the relative humidity (RH) of an area. RH is defined as the ratio of the partial pressure (or density) of water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature and total pressure (Stein and Reynolds, 2000). To maintain comfort at high air temperatures (approaching the average skin temperature of 34 $^{\circ C}$), evaporative heat loss is critical.

Human occupants are more sensitive to temperature changes than relative humidity (James and Christian, 2012), and there is little solid evidence that either high or low humidity is harmful to typical people's health. However, other research (e.g. (Klein and Schlenger, 2017) suggest that when exposed to low relative humidity circumstances, humans may get dry and irritated skin, owing to an increase in evaporation rate from the skin. A research on thermal comfort at high relative humidity done by (Arens et al., 2002) found no significant psychological or physiological differences in human reaction to exposure to 60 to 90 percent relative humidity over the temperature range of 20^{oC} to 26^{oC} when sedentary.

Other environmental elements' impacts on thermal comfort have also been investigated. Auclliciens and Szokolay (2007) investigated comfort perception at various air velocities. Health and Safety Executive (HSE) (2011)discusses the effect of heat radiation on comfort. The degree to which a building adjusts the prevalent outer climate to produce a unique internal environment is defined as its thermal performance. Many elements (such as form, direction, solar radiation absorption, window-to-wall ratio, materials, and so on) influence how buildings adapt to their surroundings. According to (M. Al-Tamimi et al., 2011), heat gain from the external window amounts for 25-28 percent of overall heat gain. As a result, window location has a significant impact on the productivity and comfort of those who work in the building.

Furthermore, different materials' thermal capacities (a measure of their capacity to retain heat from the surrounding air and surfaces) respond differently to incoming solar radiation (Stein and Reynolds, 2000). A substance with a high density, such as a concrete solid block, will store more heat than a material with a low density (concrete hollow block). The quantity of radiation reflected onto building envelopes is also affected by the level of landscaping. Furthermore, a building's orientation and spatial organization influence its capacity to ventilate and receive solar radiation. Buildings should be oriented such that the longer sides intercept prevailing winds, and the shorter sides face the direction of the highest solar radiation to minimize solar gain and maximize ventilation. As a result, adequate ventilation is achieved while the heat impact of solar radiation is minimized (Koranteng and Abaitey, 2010). Chenvidyakarn (2007), Chukiatman (1998), Hyde (2013), Lechner (2015), and Sumanon (2004) have claimed that shade has a good impact on building comfort and energy performance. In terms of thermal comfort, there have been enormous contributions to this field of study. According to research, inhabitants are willing to endure a temperature range that exceeds the ASHRAE comfort zone. This is sometimes linked to people's innate proclivity to adapt to shifting environmental conditions, as well as acclimatization. There have been very few studies in Egypt. As a result, there is a need to contribute to the expanding body of information about thermal comfort in buildings. Under the current circumstances, the purpose of this research on comfort in school buildings is to investigate occupant perceptions of the acceptable degree of indoor thermal comfort and to validate the findings against ASHRAE Standard 55.

2.2.2 Indices for Evaluation of General Thermal comfort

Several metrics for assessing human thermal response to climatic conditions or stresses have been proposed in the scientific literature over the last decades, and a number of authors have used, and continue to use, terms like discomfort index, stress index, or heat index to identify analytical models that describe the human thermal perception of the thermal environment to which an individual or a group of people is exposed. Recently, in the scientific literature, standards, and guidelines, a new form of discomfort index has been developed, primarily for concisely characterizing long-term thermal comfort conditions in buildings and forecasting unpleasant events, particularly summer overheating(Carlucci, 2013). Most of these new indices summarize a building's thermal performance to a single value. These indices may be valuable tools for conducting an operational assessment of an existing building's thermal comfort performance or for directing the optimization phase of the design of a building envelope, its thermal plant systems, and control techniques. With zero energy—primarily passive—buildings, the ability to differentiate and rank building types by comparing energy use is not sufficiently practicable (ideally the best variants will all have energy consumption values grouped in a small interval around zero). We believe that the ranking of these variations should be based on optimizing the thermal comfort performances of the envelope, passive systems, and control techniques. This is similar to lowering energy requirements (and hence energy consumption of active systems, if present) for reaching comfort design goals, but it is more flexible.

The indices that based on the heat balance of the human body often combine physiological parameters (e.g., skin wetness and mean skin temperature), behavioral parameters (e.g., the metabolic rate related to activity and thermal resistance of clothing), and thermal environment parameters (e.g., dry-bulb air temperature, mean radiant temperature evaluated in a representative position of a room, relative humidity or wet-bulb temperature, air velocity, etc.)(Carlucci, 2013). Most of these indices were created by correlating the thermal feelings of persons placed in thermostatic chambers wearing various clothing ensembles and performing various activities under a range of environmental circumstances (air temperature, humidity, airspeed, and mean radiant temperature). The thermal comfort standard specified by ISO 7730 was the first to be utilized on a global scale (Persily, 2015). Several models exist in the literature that relate the human feeling of comfort to those characteristics. In one fundamental form, the human body has been seen as an inert object capable of exchanging energy with its surroundings via convection, radiation, and conduction, as well as losing heat via evaporation and responding to conditions via the body regulating system (Hutcheon et al., 1983). ASHRAE, which created the initial comfort index based on effective temperature, has long been interested in predicting thermal comfort. Later, a new effective temperature was defined at 50% relative humidity, which identifies the uniform temperature of a radiantly black enclosure at 50% relative humidity in which the occupant would experience the same comfort, heat exchange and physiological strain as in the actual environment with the same air motion (ASHRAE, 2004). Fanger (1970) created a well-known comfort model based on two indices: predicted mean vote (PMV) and PPD.

Many comfort studies have been conducted in many countries with various geographical locations and climatic zones (Chung and Tong, 1990; de Dear et al., 1991; Fanger, 1970; Tanabe and Kimura, 1994). When these investigations are compared to Fanger's equation prediction of comfort, there is no substantial variation between comfort needs in different climatic zones. Humans, for example, do not tend to prefer higher temperatures due to their year-round exposure to hot and humid settings.

2.2.2.1 Predicted Mean Vote

The Fanger-based technique, also known as the heat-balance approach, is based on climate chamber studies and is subsequently hypothesized into the PMV-PPD model. Fanger first proposed it in the 1970s, with around 1296 persons clothed in standardized clothing and completing standardized activities, resulting in a metabolic rate of 1.2 Mets or 70 W/m^2 (Simons et al., 2014). PMV is a measure used to estimate thermal comfort in an inhabited zone based on metabolic rate, clothing, and airspeed, in addition to temperature and humidity. PMV values are based on the ASHRAE thermal sensation scale (Holmes and Hacker, 2007), which goes from -3 to 3, as shown below: 3 denotes hot, 2 denotes warm, 1 denotes somewhat warm, 0 denotes neutral, -1 denotes slightly cool, -2 denotes cool, and -3 denotes cold. ISO 7730 offered three categories, A, B, and C, but did not clarify their scope. Their boundaries are represented in terms of PMV and are the same in value as those of EN 15251: PMV for Category A is comprised in the interval [-0.2, +0.2], PMV for Category B is comprised in the interval [-0.5, +0.5], and PMV for Category C is comprised in the interval [-0.7, +0.7]. The target comfort category or acceptability range must be chosen based on

• the level of thermal comfort acceptability required in a building for ASHRAE 55,

• the intervention typology (new building or refurbishment) for EN 15251, and

• if very low variations of indoor environmental parameters are required for ASHRAE 55and EN 15251.

Fanger (1970) performed experiments with a number of people of various ages and genders in an air-conditioned environmental test room that was monitored for indoor climatic factors such as temperature, relative humidity, and so on in this study based on the First Law of Thermodynamics. Shukuya (2009), on the other hand, proposed that human body exergy balance estimates (based on the Second law) more closely describe thermal comfort than the First law. The approach comprises calculating the human body exergy consumption, HBexC, rate, and PMV using external temperature, To, and relative humidity, RHo, as well as inside environmental data. Isawa et al. (2003) revealed a correlation between thermal comfort and HBexC. Another outcome of their investigation revealed that thermal neutrality had the lowest exergy use. Similarly, Prek (2005) discovered that the lowest HBexC rates were close to neutral thermal sensation votes. Although the PMV method is reliable in air-conditioned buildings in cold climates, de Dear et al. (1997) demonstrated that occupants' acceptance range of PMV in naturally ventilated buildings in warmer climates is much wider than the standard PMV model based on objective (Ti, To, RHi, RHo, MRTi, and va) and subjective measurements.

Overall, field studies of thermal comfort (ASHRAE, 2001; Humphreys and Fergus Nicol, 2002) indicate that the PMV model does not always precisely predict occupants' actual thermal sensation. Measurement inaccuracy and contextual assumptions have been identified as two major contributors to the disparities by researchers (de Dear and Brager, 2002). Physical variable measurement with a reliable instrument, clothing insulation, activity levels, individual differences, outdoor climate, building differences, behavioral and psychological adaptation are all factors mentioned by thermal comfort researchers as contributing to the PMV model's bias nature (de Dear and Brager, 2002; Humphreys and Fergus Nicol, 2002; Morgan et al., 2002). The majority of researches found the PMV model prediction to be a better predictor in mechanically ventilated buildings (Brager and de Dear, 1998; Oseland, 1995). In the case of naturally ventilated structures, discrepancies in thermal sensations recorded by occupants and those predicted by the PMV model have been reported (Beizaee et al., 2012). According to studies, the PMV either underestimates or overestimates occupants' heat feelings. Hong et al (2009) and Han et al (2007) found that the PMV model underestimated heat sensitivity.

2.2.2.2 Predicted Percentage Dissatisfied

PPD is used to evaluate the occupant's thermal comfort satisfaction. It is thought that pleasing 80 percent of occupants is excellent: that is, PPD less than 20% is acceptable (Guan et al., 2003). Improving worker productivity, occupational health, and safety are key industrial problems, particularly in emerging nations. However, these sectors are characterized by bad workplace design, ill-structured tasks, a mismatch between workers' talents and job needs, a hostile environment, inadequate human-machine system design, and ineffective management programs (Freire et al., 2008).

Light, air quality, noise, and the temperature climate were all examined as aspects that would impact the acceptance and performance of the facilities' inhabitants. Lower emotional health is manifested as psychological anguish, sadness, and anxiety, according to (ISO 7730, 1994), whereas lower physical health is exhibited as heart illness, sleeplessness, headaches, and infections. These health issues may manifest themselves in organizational symptoms such as job discontent, absenteeism, and poor work quality. Irritation, sore eyes and throat, hoarseness, stuffy clogged nose, extreme mental exhaustion, headache, and unusual tiredness were all symptoms of poor working conditions (Fanger, 1970).

2.2.2.3 Indoor air quality

Indoor air quality (IAQ), as well as the sense of thermal comfort, have a significant influence on occupants' health and productivity. IAQ is affected by the kind and amount of contaminants such as CO, CO_2, NO_2, radon (Rn), and SO_2 (Turhan and Gokcen-Akkurt, 2018). The concentration of CO_2 is an obvious indicator of human existence. Other factors, including the condition of doors, windows, and mechanical ventilation systems, have an impact on it. As a result, these other variables have also been considered. A rise in CO_2 content activates the human respiratory system and raises met levels. The concentration level of CO_2 is mostly determined by the ventilation rate and the number of people (Lu et al., 2010). The nature of the working space and its utilization determine whether the occupancy is transit or fixed. According to ASHRAE standards, the allowed CO_2 concentration in occupied space for a safe and sanitary environment is 1000 ppm (ASHRAE, 2009). Due to continual recirculation of room air, the CO_2 content is in the 1500–1800 ppm range. Many authors (Allen et al., 2016; Coley et al., 2007; Prairie and Duarte, 2006; Riham Jaber et al., 2017) have explored the influence of ventilation rate and indoor CO_2 concentrations on metabolic rate, cognitive function, learning abilities, and classroom involvement levels. To increase IAQ, natural ventilation and constant CO_2 monitoring within the classroom were advised (Ng et al., 2011; Vilčeková et al., 2017). The only way to get fresh air in an enclosed air-conditioned area is to open a window. Wallace et al. (2002) investigated air change rates in an inhabited air-conditioned house and determined that an autonomously operated window combined with an exhaust fan improves ventilation and keeps CO_2 levels below 1000 ppm. The state of the outdoor environment is equally important in the case of ventilation by window opening (Gao et al., 2014). A review of the literature indicates that boosting fresh air ventilation and incorporating CO_2 sensors (Demand Control Ventilation) might be viable methods for decreasing CO_2 concentrations. However, both approaches result in increased energy usage and energy costs. To enhance the IAQ, a novel method of pre-cooling ambient fresh air and entrance to the conditioned environment is required.

2.3 Visual Comfort

2.3.1 Lighting

Daylighting is a passive approach for improving energy performance and user visual comfort that does not need costly installation or operation (Lim et al., 2012). Daylight is the broadest spectrum of light that is most suited to the human visual response. As a result, it can benefit human health, performance, and productivity (Cheung and Chung, 2008; Galasiu and Veitch, 2006). However, under certain circumstances, daylight may produce glaring difficulties, particularly in workplaces or other areas with a visual environment. Solar shade devices decrease glare and limit solar gains, preventing overheating (Balocco and Calzolari, 2008; Loutzenhiser et al., 2007). The precautions and criteria for good daylighting in buildings are presented in several codes (British Standard (BS), 2008; British Standards Institution (BSI), 1992), regulations (Buildings Department, HKSAR, 2005; Hong Kong Government, 1997), and design handbooks (Illuminating Engineering Society of North America (IESNA), 1993). The US Green Building Council's LEED-NC (2009)(2009) green building rating system recommends a daylight factor (DF) of 2% for the minimum daylight level and a minimum illuminance level of 269 lx on the equinox at 9 a.m. and 3 p.m. under International Commission on Illumination (CIE) clear sky circumstances. The BREEAM environmental evaluation method gives a credit when occupied spaces have an average

DF of more than 2%. IESNA (2011) committee recommends an illuminance level of 300 lx for offices, classrooms, and library-type areas that are occupied between the hours of 8 a.m. and 6 p.m. local clock time. Illuminance uniformity is an important criteria in daylighting. A requirement for illuminance homogeneity is commonly included in general guidelines (e.g., minimum to average of 0.7 over the area of work). According to the Chartered Institution of Building Services Engineers (CIBSE)(2006), the minimum illuminance level in educational buildings is 300 lx for classrooms and computer practice rooms, 750 lx for technical drawing classrooms, and 500 lx for conference and meeting rooms. Perez et al. (1990) suggested a meteorological model to quantify luminous and external illuminance efficiency. The illuminance is described in point-to-point calculations using the DF.

2.3.1.1 Effects of windows on daylight

Windows have a significant influence on environmental aspects including thermal comfort, fresh air supply, energy efficiency, and noise intrusion. As a result, windows may be seen as a sophisticated component of architectural design and need to be properly studied (Building Bulletin 90, 1999). One of the most important tactics for efficiently decreasing energy consumption in a building is the design and selection of a proper window system (Lee et al., 2013). The two most challenging design characteristics are window size and disposition, because they must integrate all of the human variables, such as providing a view, controlling heat gain and loss, and eliminating glare, as well as the more obvious demands of functional eyesight. In most cases, sufficient daylight is only accessible up to twice the height of the window head height above the working plane into a room (CLEAR, 2012). A large window area allows more light into a place and maximizes sunlight usage. They may, however, result in excessive heat gains or losses, increasing energy usage (Ghisi and Tinker, 2005). Although a small window size does not affect daylighting efficacy, it does help with thermal insulation and reduces cooling demands (Li, 2010). When compared to the exterior horizontal daylight illuminance, daylight in a one-sided window room is likely to be more approximately proportionate to the quantity of daylight falling on the window (Li, 2010). Zain et al.

(2002) investigated the effect of window geometry on daylighting in a tropical Malaysian environment. According to their research, the optimal opening for daylight was 25% of the window-to-wall ratio. According to Ne'eman and Hopkinson (1970), the combined windows should give an average of 5% DF over a significant portion of the floor space. From the architect's perspective, this may appear to be the most crucial decision in establishing how the building elevations would appear from the outside. However, from a strategic standpoint, it will decide the success of the daylight-based design strategy.

2.4 Model Simplification

Currently, there are several building energy simulation programs on the market that are utilized for energy optimization of buildings, heating networks, and district heating substations. These programs differ in terms of their capabilities, the quality of the results obtained, and the amount of sophistication. In many situations, the latter restricts the use of these programs to highly educated engineers. Furthermore, professional software, particularly Building Information Modelling type systems, is very expensive to acquire and maintain, making it difficult, if not impossible, for smaller offices to employ it. Simplified models are a quick tool for energy assessment, and that is the main reason for many countries to adopt this approach in their building energy regulations. Quantifying the uncertainty in simplified models is essential to assure that building energy labeling processes will achieve the desired results. The time consumed on modeling tasks is one of the reasons that implies the discrete use of building simulation tools by design offices. This issue can be softened by a more accurate calibration of the model and uncertainty analysis over input parameters. Some researchers have explored calibration methodologies and reported their experiences in the simulation of existent buildings.

Several studies have examined the effect of model simplification on the result accuracy. Amitrano et al. (2014) investigated the effect of the level of detail on the accuracy of the energy simulation in office buildings. Their study concluded that more detailed geometry could enhance the reliability of simulation by 5 to 15%. Picco and

Marengo (2015) assessed the effect of different simplifications in building construction types, thermal zoning, and building obstructions, for instance. The findings showed that strong simplifications on the building geometries do not make a significant change on the outputs, compared to the detailed model. Bosscha (2013) applied a sensitivity analysis by varying the material properties, geometry, heating, ventilation, and HVAC settings to compare the accuracy of the calculations with the detailed model. The results concluded that the increase in accuracy obtained by more detailed zoning and geometry is highly relying on the HVAC simulation type. Korolija and Zhang (2013) compared the predicted annual energy use of the detailed model in which every room was modeled as a separate zone with a simplified model, in which each floor is was modeled as a single zone. The output results showed that thermal zoning simplifications decreased the simulation time by 30% and the mean absolute error of annual heating demand was 10.6%. Klimczak et al. (2018) explored the effect of model simplifications on the quality of energy simulation results of a residential building case. The simplifications consisted of the reduction of thermal zones and internal walls, removal of shading elements, and calculations were carried out in different iterations. The findings showed that the exclusion of the shading devices on the south façade had a considerable effect, thus, in future studies, this simplification should not be applied. Heo (2016) estimated the impacts of internal load, scheduling, and thermal zoning simplifications for domestic buildings in the United Kingdom. They concluded that the differences in annual heating demand are 26% and 17% in the simplification with one single zone for the entire dwelling and one thermal zone per floor, respectively. Dipasquale et al. (2013) studied the impact of defining the physical and geometric characteristics of buildings, such as the presence of internal walls, thermal capacity, thermal bridges, the gross or net surfaces, and the number of zones during the modeling stage for heat load assessment. The findings of these results concluded that the reduction of the number of zones has the highest effect on the loads, almost 22% in the cooling demand and 12.5% in heating demand. Chatzivasileiadi et al. (2018) explored the impact of simplifying the complex geometries through a systematic analysis of different test cases on the accuracy of energy performance simulation results. The results concluded that orthogonal prisms as simplified surrogates for buildings should be avoided where it is possible, as it showed the worst-case scenario. Akkurt et al. (2020) concluded that the simplification of geometry is often unavoidable for use in building-energy performance simulation, but inaccuracies resulted from oversimplification in some geometrical characteristics must be avoided. Zhao et al. (2018) investigated the appropriate level of geometric modeling simplification through the thermal zone, typical floor, and fenestration in energy analysis for office buildings and they found that the more accurate case is modeling the exterior wall in regarding to internal edge. Samuelson et al. (2016) assessed the accuracy of 18 design-phase building-energy models to enhance the simulation predictions compared to measured energy data.

2.5 Sensitivity Analysis

Sensitivity analysis is the study of the effects of changes in parameters of a mathematical model or system on the outputs or performance of the system. In other words, sensitivity analysis may be used to assign changes in a system's outputs to various sources of uncertainty in its inputs. Sensitivity analysis identifies the most important design parameters in terms of building performance. In practice, uncertainty and sensitivity analysis provide a number of additional advantages, including: (1) the use of parameter screening to simplify models (De Wit, 1997; Elhadad et al., 2020); (2) the evaluation of models' robustness (Litko, 2005); (3) alerting designers to unexpected sensitivities that may result in errors, and/or incorrect specifications (quality assurance) (C. Hopfe et al., 2007; Hopfe et al., 2006; C. J. Hopfe et al., 2007; Hopfe, 2009; Lewandowska et al., 2004); and (4) providing a "what-if analysis" by changing the input parameters and displaying the effect on the outcome of a model (decision-support) (Gokhale, 2009). By focusing on the most influential parameters, the number of parameters to be estimated using in situ measurements can be reduced. Furthermore, it significantly reduces the computational requirements of inverse problems (Beck and Arnold, 1977). The objective function was set to help with previously unmeasured existing buildings, especially with the historical or pronounced architectural value.

2. 4.1 Sensitivity analysis applications

The application of sensitivity analysis is an appealing method for highlighting the main parameters and their effect on the model outputs. Several studies in the literature were conducted on sensitivity analysis methodologies in the simulation of building energy. Goffart et al. (2017) applied the uncertainty analysis to evaluate the effects of bricks on the energy cooling demand of a structure. Yu et al. (2013) conducted an energy performance sensitivity analysis to evaluate the effects of eight design parameters and defined the most important parameters for various WWR. Eisenhower et al. (2012) proposed a sensitivity indices decomposition to identify which intermediate processes (e.g., heating sources, cooling sources air handling unit, etc.) made a significant contribution to the uncertainty of building simulation outputs. Spitz et al. (2012) utilized 6669 simulation runs of the variance-based Sobol method to find the most significant factors for an experimental home in France. The design variables that have the largest effect on a typical office building's energy performance are determined in (Mechri et al., 2010). Hopfe and Hensen (2011) conducted sensitivity and uncertainty analysis on three types of office building input parameters: design parameters, physical parameters, and scenario parameters. Heiselberg et al. (2009) applied a local sensitivity method, the Morris method (Morris, 1991), to perform sensitivity analysis on office buildings in Denmark to assess the impact of design parameters on total building energy demand. Heo et al. (2015) used the Morris design technique to describe the ranking of energy usage intensity for office buildings in Chicago's commercial center. Tian and Choudhary (2012) utilized the standardized regression coefficient (SRC) technique to identify the major parameters influencing energy use in London school buildings. Song et al. (2014) used a treed-based Bayesian Gaussian model (one of the meta-modeling sensitivity analysis approaches) to analyze the energy usage trends of a London office building.

CHAPTER Three

3. PASSIVE DESIGN STRATEGIES FOR RESIDENTIAL BUILDINGS IN A HOT DESERT CLIMATE

Egypt is characterized by a hot desert climate. Most of the residential building occupants suffer from indoor environments because of the high indoor Temperature and the majority of buildings have a poor design related to the climate. This Chapter investigates different passive design strategies to enhance the energy-efficient design and increase the performance of thermal comfort in a typical residential building in New Minia, Egypt. The approaches are conducted by computational IDA ICE 4.7.1 program to simulate different scenarios. The Passive design strategy is relying on the building geometry, site and climate conditions. It is considered as one of the most effective approaches to enhance occupants' thermal comfort and reduce the energy consumption of the building. Several scenarios of passive design were applied, including thermal insulation, glazing pane, form compactness, infiltration, and fixed shading.

3.1 Introduction

The residential buildings represent a large proportion of the building sector, which have a direct relationship with human life and the environment. In many of developing countries, especially those characterized by a hot and dry climate, special issues emerging in urban areas due to the heat retention of buildings (Akande, 2010; Weihe, 1985). Most of the residential buildings in these regions are not suitable for occupants due to the improper design of building-related to the climate. Energy loads in new residential buildings are increased because of improper use of building materials (B. Hanna, 2004). Human behavior plays a critical role in energy performance through the way of using appliances (Elhadad et al., 2019a, 2019b). Most of the residential buildings' façades in Egypt were exposed to high daytime temperatures and suffered from indoor environments because of the high indoor temperature and the poor design related to the climate.

Passive design is the main key for sustainable buildings. It depends on the building geometry, site and local climate conditions to minimize the energy consumption and maximize the thermal comfort of the building through enhancing indoor air quality. Thus, the efficient passive design of buildings is to take the best advantage of the local conditions (Kang et al., 2015; Wu and Thomas, 2007). Passive design solutions primarily address the thermal characteristics and airtightness of building envelopes, which include walls, outside windows, and roofs. These technologies may include enhanced insulating materials for building envelopes, window systems, and exterior and interior shadings (O' Donovan et al., 2021; Qu et al., 2021; Stritih et al., 2018; Wang et al., 2021). Passive buildings that are well-designed preserve the optimal environment for human habitation while decreasing energy costs. Passive design techniques provide longer life spans, lower life cycle costs, and larger energy savings advantages when compared to active strategies (Dahlstrøm et al., 2012; Yu et al., 2020). The primary design issue is including components that reduce interior heat gains and ensure thermal comfort of occupants during periods of strong solar radiation. . According to Hyde (2013) passive building design is important in hot climates since traditional energy sources are limited in terms of both cost and availability

Building orientation, thermal insulation, building shape, window frame and glazing, air infiltration, and shading device control represent the most important factors for the optimal design of passive building solutions (Iwan, 2014). WWR is one of the key parameters in the glazing system design. WWR for many of high-performing buildings accounted to (25 to 35 %) (Hootman, 2013). Moreover, when the outdoor climate is uncomfortable, the natural ventilation improves indoor thermal comfort by providing fresh air (Dehghani-sanij et al., 2015). A wind tower is still used in some regions of the Middle East and Egypt as a passive cooling strategy for ventilation and cooling the buildings (Bainbridge and Haggard, 2011). This chapter investigates the passive design strategies that can comply with the climatic region to enhance the thermal comfort of the building and to decrease energy consumption.

3.2 Materials and Methods

3.2.1 Case Study

The study area is situated in New Minia, Egypt at latitude 28.08N, longitude 30.73E. The dwelling is a residential building for the householder. It is a four-story building with a total floor area of 150 m^2 on each floor. Every floor has one apartment which consists of 8 rooms and a courtyard as shown in Figure 3-1.

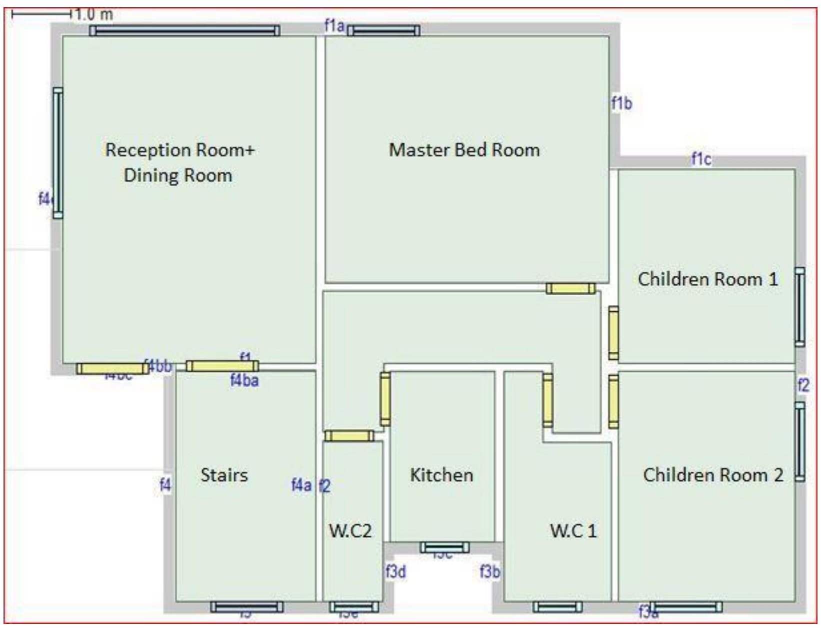


Figure 3-1. Floor plan of the dwelling object of study.

Egypt is located in the dry and hot climatic zone. The average monthly dry-bulb temperate and relative humidity are shown in Figure 3-2. The highest temperature was observed in July with an average value of 29.8 while January represents the coldest month with an average temperature of 12.7 °C. The relative humidity ranges between 40.1 % and 67.1 % with an average value of 54.2%.

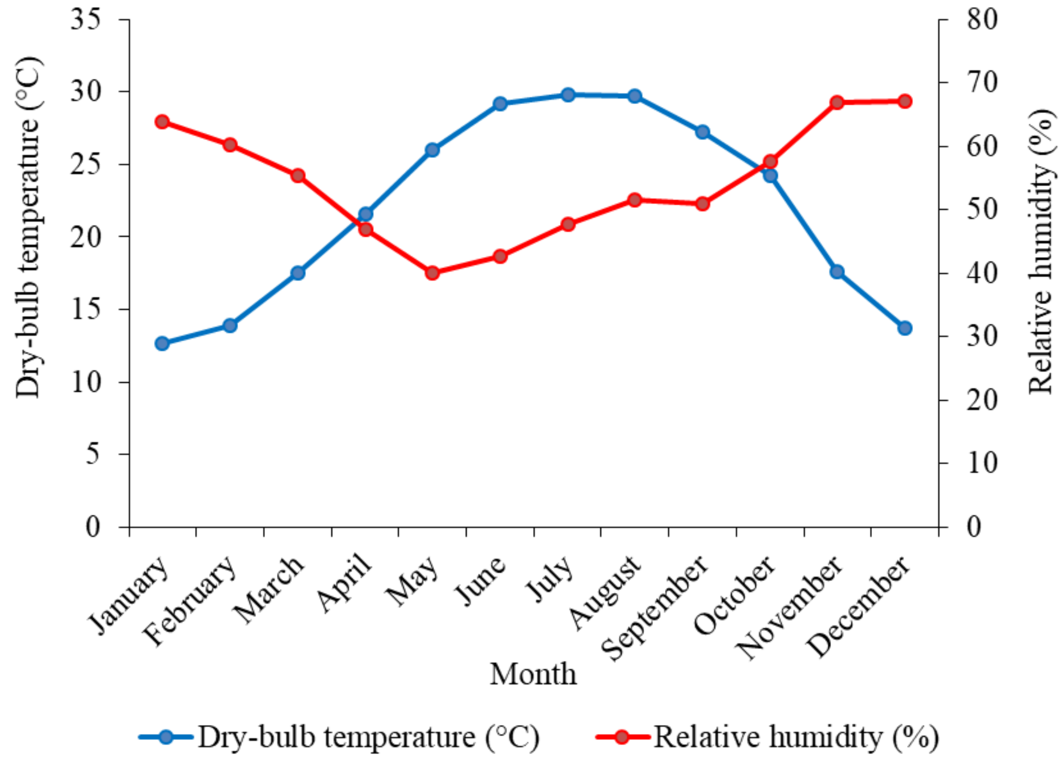


Figure 3-2. Average monthly air temperature and relative humidity.

3.2.2 Reviewing the construction materials according to the Egyptian *standards*

The first stage started by reviewing the material properties of buildings based on Egyptian standards. Attia and Wanas (2012) introduced the thermal properties of Egyptian building materials. Table 3-1 shows the composition of building elements used in the case study through building materials, thickness, and thermal transmittance coefficient (U-value).

Table 3-1. Building envelope properties.

Element	**Building Materials**	**Thickness (m)**	**U value (w/(m²*k)**
External wall	**5mm Plaster+25mm Egyptian Portland cement mortar+ 250mm Double red**	0.31	0.79

	brick+25mm Egyptian Portland cement mortar+5mm Plaster		
Internal wall	**5mm Plaster+25mm Egyptian Portland cement mortar+125mm Single red brick+25mm Egyptian Portland cement mortar+5mm Plaster**	0.185	0.95
Internal floor	**10mm Concrete tiles+20mm Egyptian Portland cement mortar+50mm Sand+200mm Plain concrete**	0.28	1.824
Roof	**10mm Concrete tiles+20mm Egyptian Portland cement mortar+50mm Sand+20mm Betomine damp insulation+150mm Rein force concrete**	0.25	1.71
External floor	**10mm Concrete tiles+50mm Sand+20mm Egyptian Portland cement mortar+200mm Plain concrete+250mm Soil**	0.71	1.172
Glazing	**20mm Single glazed glass**	0.02	5.0

3.2.3 Conducting a field survey of the existing building

The second stage was carried out by conducting a field survey in New Minia city, one of the newly constructed cities. The construction of New Minia city has started in 2004, the city is located east of the Nile in front of the old city and 250 km from the capital (Cairo). The total area is about 100 km^2 and the urban mass is about 26.5 km^2 (residential areas, service, industrial, tourist, and recreational). Regarding to the housing sector: the total number of units in the city are about 41.544 units about 22.722 units (constructed and under construction) owned by the government, about 18.822 residential units were constructed by the private sector, the government, and others. Figure 3-3 presents the different topologies that constructed in the residential buildings of the city.

Figure 3-3. The different residential typologies in New Minia City.

3.2.4 Simulation building tool

Among several simulation tools, Indoor Climate and Energy (IDA ICE 4.7) was applied to assess the energy performance and the indoor climate of buildings in this study. IDA ICE simulation software is licensed; the faculty of Engineering and Information Technology, University of Pécs has the educational version for multiple users. IDA ICE is an innovative and dynamic multi-zone simulation application to evaluate the energy consumption and thermal indoor climate of the entire building.

3.3 Results and Discussions

3.3.1 Energy performance analysis in the Residential building

The materials used for constructing walls, floors, roofs, and their thickness, as well as window panes collected by reviewing the material properties of buildings based on the Egyptian standards (Attia and Wanas, 2012). For the investigated area, the optimal orientation for this building is the North façade(Elhadad et al., 2018). The energy analysis for the optimal orientation of the building is shown in Table 3-2. The total delivered energy of the building annually was 150991 kWh and requires around 225.5 kWh/m^2. The majority of energy is attributed to cooling demand by 96123 Kwh (63.66% of total energy demand) while the heating is represented by 29689 Kwh (19.66 %of total energy demand).

Table 3-2. Total supplied energy.

	Delivered energy		%
	Kwh	**KWh/m^2**	
Lighting, facility	9191	12	6.09
Electric cooling	96123	125.8	63.66
HVAC aux	0	0	0.0
Electric heating	29689	38.9	19.66
DHW	4246	5.6	2.81
Equipment, tenant	11742	15.4	7.78
Total	150991	197.7	100.0

3.3.2 Passive Strategies Optimization

After performing the energy analysis for the base model, the first step in the optimization process is to select the applicable passive strategies scenarios which include thermal insulation, fixed shading, infiltration, glazing pane (Table 3-3). The simulation results have been shown in Table 3-4. The positive value represented the positive point, and the negative value represented the negative point. Adding 20 cm insulation in the building envelopes, the energy consumption was saved by 25% compared to the base case reduced significantly for both, while the acceptable hours for the thermal comfort hours was decreased.

By reducing the air infiltration from 7 ACH to 0.5 ACH, the energy consumption was slightly decreased, while the CO_2 level was increased by 40% regarding to the base model. Replacing single-pane glazing to triple-pane glazing, the energy consumption was reduced significantly while the acceptable hours for the thermal comfort hours were slightly increased.

Table 3-3. Description of passive strategies scenarios.

Scenarios	Description
Scenario (1)	Adding 20 cm thermal insulation to the building envelopes.
Scenario (2)	Applying fixed shading for the windows on the south façade.
Scenario (3)	Reducing air infiltration from 7 ACH to 0.5 ACH
Scenario (4)	Replacing single-pane glazing to triple-pane glazing.
Scenario (5)	Implementing the most effective scenarios together

Table 3-4. The percentage of reduction and increased energy consumption and thermal comfort in all scenarios.

Parameter	Units	Base	Scenario_1	Scenario_2	Scenario_3	Scenario_4
				%		
Max. heating load	(W)	0.0	-25	-26	-3	-4.6
Max. cooling load	(W)	0.0	-19.4	-24	-0.8	-10
Heating demand	(Kwh)	0.0	-40.1	-28	-0.6	-28
Cooling demand	(Kwh)	0.0	18.2	-18	0.7	-48
Co2	(Ppm)	0.0	-1.2	0.0	45	2.2
Daylight	(Lux)	0.0	0.0	-26	0.2	-39
Acceotal thermal comfort	(Hour)	0.0	-2	2.6	2.2	2.6

Based on the analysis of scenarios results, the most effective strategies for reducing energy consumption were triple pane glass followed by thermal insulation, infiltration, and fixed shading, While the most effective strategies for thermal comfort were triple pane glass, and fixed shading. In general, the infiltration strategy represents the least effect on energy consumption and thermal comfort performance.

3.4 Summary

In the past few years, energy consumption has increased sharply in Egypt and passive strategies are desperately required to reduce energy consumption and to improve thermal comfort, indoor air quality. This paper presents approaches to explore reducing energy consumption and increasing thermal comfort performance for residential buildings in New Minia, Egypt through investigating different passive strategies. The different scenarios of passive strategies include thermal insulation, fixed shading, infiltration, glazing pane are simulated by computational IDA ICE 4.7. The results show that the most effective passive strategies were thermal insulation and adding extra panes of glazing . On the other hand, infiltration represents the least effective passive strategy, thus, it is not recommended for building in a hot and arid climate. This study concluded that adopting certain passive design strategies can reduce the energy for cooling and increase the thermal comfort performance.

CHAPTER Four

4. THE IMPACT OF BUILDING ORIENTATION ON ENERGY PERFORMANCE

The passive design aspects provide ideal comfort while reducing the need for mechanical equipment within the structure for cooling and heating. Orientation and building envelope are considered one of the most fundamental design features of energy-efficient buildings. Thus, this chapter focused on the effect of building orientation on energy consumption. In the framework of thermal simulation, a case study of a residential building in a hot climate is investigated

4.1 Introduction

Nowadays the world buildings sector accounted for 40% of the total world's energy consumption, in which the residential buildings are responsible for two-thirds and the commercial ones for one-third, according to the Economic Cooperation and Development Organization (ECDO) (Nassief, 2014). Boake (2009)mentioned that buildings are accounted for about 40%-70% of global carbon dioxide emissions. Therefore, there is a tendency for expectation to reduce the energy consumption by energy-efficient building design methods to consume less energy all over the world

In Egypt, energy consumption increases due to growing populations. The energy demand in Egypt has increased by 7.5% per year (Annual Report 2011/2012, 2013). This increment is crucial compared to the annual average world's growth in energy consumption of 2.6% (Setiawan et al., 2015); where the household sector is the biggest consumer of energy contributed by 43.3% (Annual Report 2013/2014, 2015); the industry accounted by 28.4%; commercial buildings 10.4%; and the energy used for street lighting and agriculture is equivalent to 4.4% (B. Hanna, 2015). The energy demand of a building depends on several design factors that can be optimized, like transparency ratio, orientation, shape factor, thermal and physical properties of building materials. Several previous studies investigated that the building orientation is one of the most important parameters for energy efficient design and thermal comfort as the orientation is a primary parameter that influences the percentage of sun radiation exposed to the building, on ventilation, on thermal comfort, and lighting.

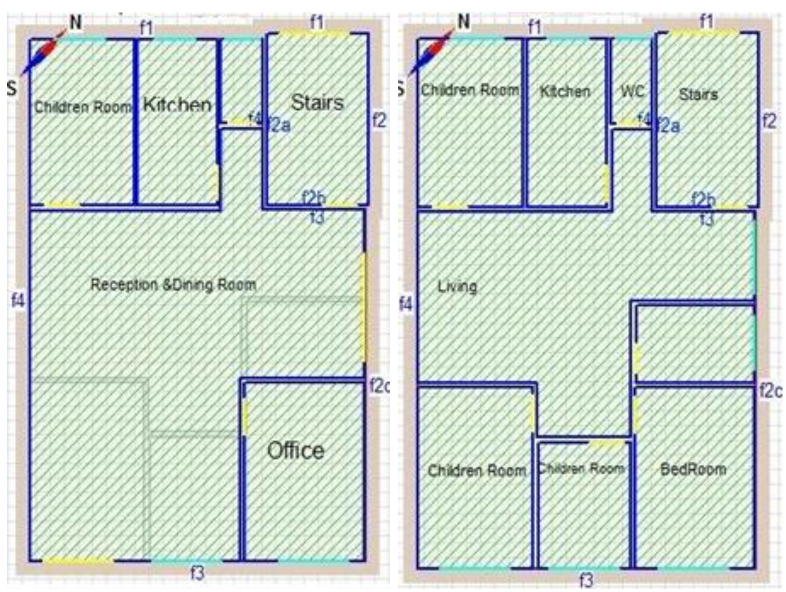
The orientation of the site must be considered when planning a building; this has an impact on the building design since it helps to enhance the efficiency of various passive cooling measures. Buildings that are properly oriented take advantage of solar radiation and prevailing wind. Ahmeti et al. (2017) studied the energy consumption of the residential sector in the city of Prishtina, Kosovo by using the energy management method. Váradi-Varga and Kistelegdi (2014) discussed the possibility to apply energy performance modernization in 'Squirell Garden' Nursery School in Csurgó, Hungary by enhancing the comfort level of children and teachers in the nursery school. Baranyai et al. (2013) stated the applicability of the 'Energy design Roadmap' method for planning smart energy-plus buildings. Kiss and Reith (2013) tested the ways of reducing energy consumption in cities through different urban and architectural tools and also, analyzed the possibilities of using renewable energy sources in cities.

Jaber and Ajib (2011) assessed the optimal orientation of the building, windows size, thermal insulation thickness for residential buildings. Morrissey et al. (2011) discussed the passive solar design in moderate climates; Friess and Rakhshan (2017) studied several measures of passive design to enhance energy efficiency in the United Arab Emirates. Therefore, the main aim of this study is to analyze and quantify the importance of the building orientation to provide appropriate thermal comfort and high energy performance for the building that leads to reduce the energy consumption of the dwelling. Also, study the impact of the location of the building, especially when the latitude and weather are different through (Cairo, Aswan, and Alexandria) on energy consumption.

4.2 Materials and Methods

4.2.1 Building data

The building analyzed through this paper is located in Minia, Egypt about 250 km from Cairo at latitude 28.08 N, longitude 30.73 E, the case study building is a family house, which was built in 2016. It is a two-story building with a total floor area of 300 m^2, with a volume of 980 m^3. It consists of 9 rooms and a courtyard. Figure 4-1 shows the indication of the room's distribution and the location of the main entrance in the façade of the floor plan and the first floor of the dwelling.

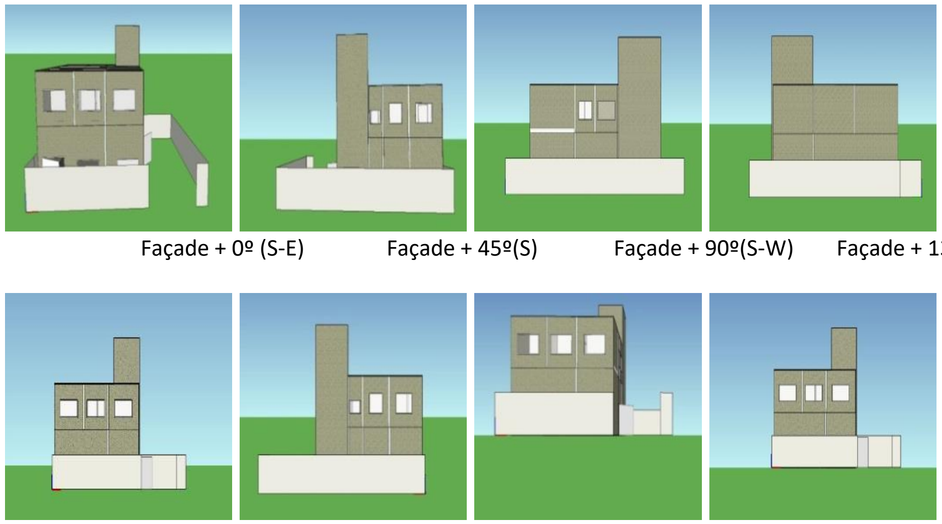


First-floor Second floor

Figure 4-1. Building zones for the first and second-floor plan of the dwelling object of study.

4.2.2 Methodology

Eight simulations were applied by changing the orientation by 45º among them, setting the existing building facade orientation (south-east) as a reference. Figure 4-2 represents this procedure. After this, the total energy demand for cooling, heating, and lighting was calculated for each case using IDA ICE 4.7 simulation tool.



Façade + 0º (S-E) Façade + 45º(S) Façade + 90º(S-W) Façade + 135º(W)

Façade+180º(W-N) Façade + 225º(N) Façade + 270º(N-E) Façade + 315º(E)

Figure 4-2. Building simulation for each orientation

4.3 Results and Discussion

4.3.1 Energy analysis of the existing situation

The main façade of the building faces south-east. The total delivered energy of the existing building annually was 52560 kWh. The following Table 4-1 shows the delivered energy for the current situation relying on final use. The energy is mostly used for cooling demand by 74.46% of the total delivered energy, secondly heating demand, which represented by 12.20% of total energy and the rest was accounted for 13.34% of total energy.

Table 4-1. Results of the existing situation (façade oriented to S-E)

Delivered Energy	Existing (S-E), KWh
Lighting	**2766**
Cooling	**39137**
Heating	**6411**
Domestic Hot water	**4246**
Total	**52560**

Regarding to the variation of cooling and heating demand during the simulation year, this trend is represented in the following Figure 4-3.

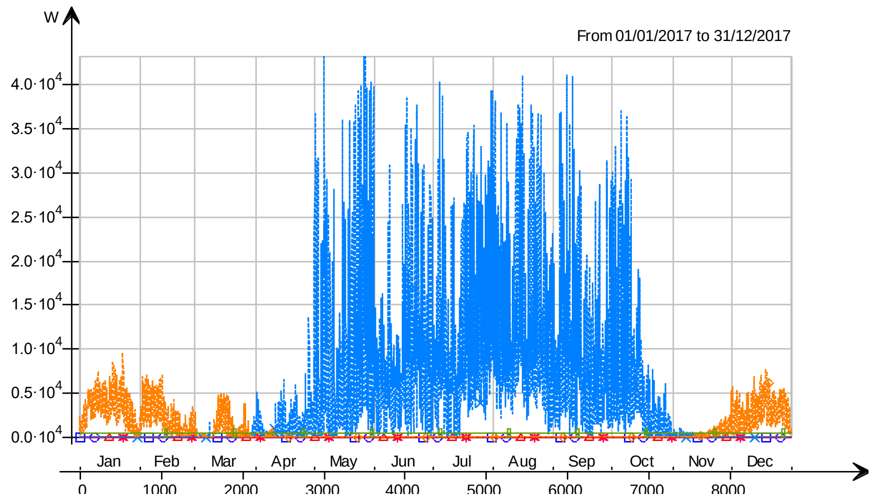


Figure 4-3. Cooling and heating demand during the simulation year.

4.3.2 Energy analysis for all orientations

Figure 4-4 shows the delivered energy for each orientation, to understand how they vary through varying this parameter. The majority of the cooling demand accounted from May to October. On the other hand, heating demand represented from November to March (Figure 4-3). The results show that only heating and cooling demand change relying on the orientation of the building and very small variation in delivered energy for domestic hot water and lighting with orientation. It can be observed that the highest energy consumption for cooling demand and this complies with climate condition in the case study.

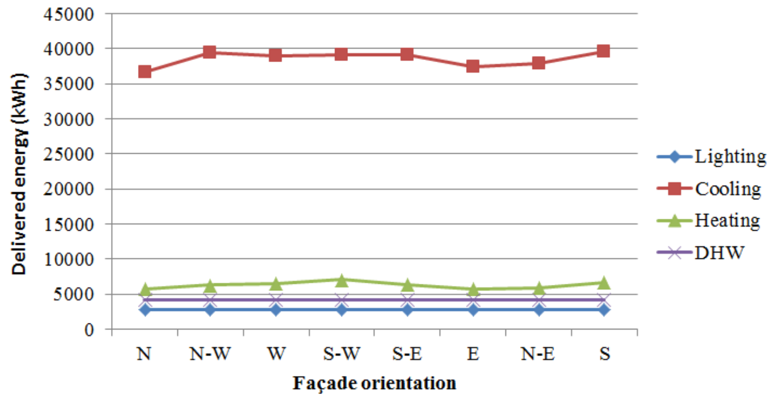


Figure 4-4. Variation of delivered energy with the façade orientation

As it is shown in Figure 4-5 the total delivered energy for cooling and heating are minimum for northern orientation and the remaining delivered energy are the same for all orientations therefore the optimal orientation related to energy consumption is north Façade. In contrast, the south façade represents the worst orientation that consumes the largest amount of energy. In an arid climate, in which the cooling demand requires the largest amount of energy the north orientation is more efficient for energy consumption.

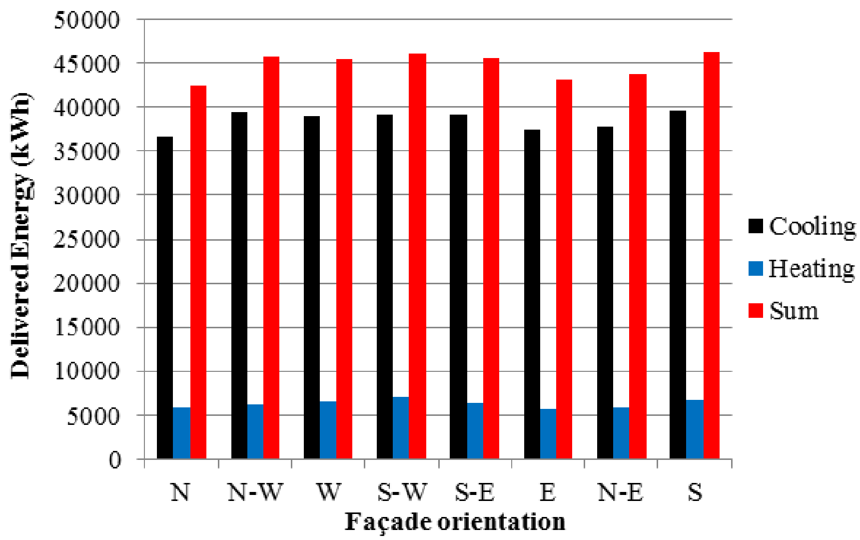


Figure 4-5. Delivered energy for heating, cooling, and the combination of both for each orientation

Table 4-2 introduces the differences in delivered energy between the best and existing orientations found for this building. The difference between optimal and existing orientation is 3052 kWh annually, where the major difference in cooling demand by 2456 out of 3052 is about 80 %.

Table 4-2. Difference in delivered energy between N (best) and S-E (existing) orientation.

Delivered Energy	Best (N), kWh	Existing (S-E), kWh	Difference, kWh
Lighting	**2765**	**2766**	**-1**
Cooling	**36681**	**39137**	**-2456 (6.7%)**
Heating	**5816**	**6411**	**-595**
Domestic Hot water	**4246**	**4246**	**0**
Total	**49508**	**52560**	**-3052 (5.8%)**

Table 4-3 depicts the differences in energy consumption between the best and worst orientations for this dwelling. The difference between the best and worst orientation is 3727 kWh for one year which is 7.5 % saving in energy consumption, which the major difference in cooling demand by 2863 out of 3727.

Table 4-3. Difference in delivered energy between N (best) and S (worst) orientation.

Delivered Energy	Best (north),(Kwh)	Worst (south),(Kwh)	Difference(Kwh)
Lighting	**2765**	**2766**	**-1**
Cooling	**36681**	**39544**	**-2863**
Heating	**5816**	**6679**	**-863**
Domestic Hot water	**4246**	**4246**	**0**
Total	**49508**	**53235**	**-3727**

4.3.3 Impact of building location on energy consumption

In the next phase of the study the impact of building location on energy consumption was investigated through three different climatic regions: Cairo, Alexandria, and Aswan cities as shown in Figure 4-6 with different latitudes 30.1, 31.2, and 24 respectively. Aswan represents a very hot and arid region and Alexandria represents a coastal area with more humidity and moderate summer temperatures.

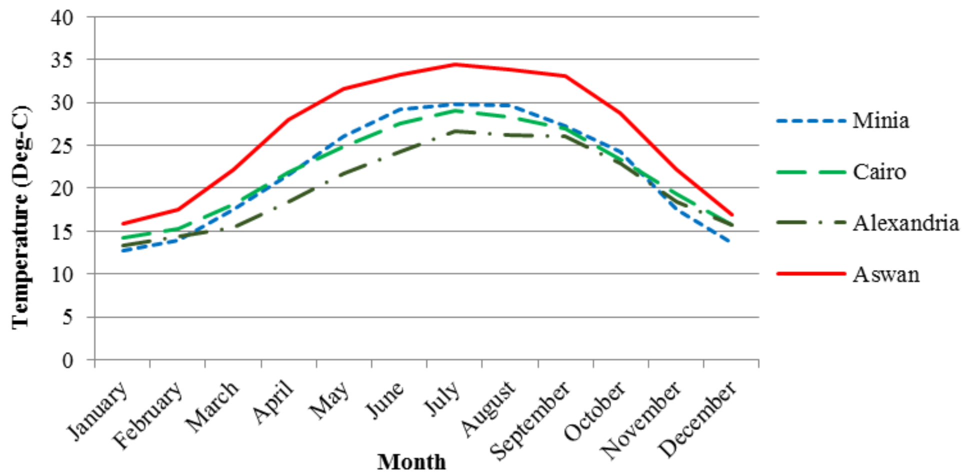


Figure 4-6. Variation of temperature during a year for four cities.

Analysis of energy performance made for 4 locations with different climate conditions to achieve all objectives. As it can be observed in Figure 4-7, energy consumption is very much affected by the location of the actual dwelling. Alexandria (coastal area) represents the minimum energy consumption by 41906 kWh per year. In contrast, the energy consumption is maximum in Aswan (a very hot area) by 91555 kWh per year up to 42 % compared to the case study (Minia city).

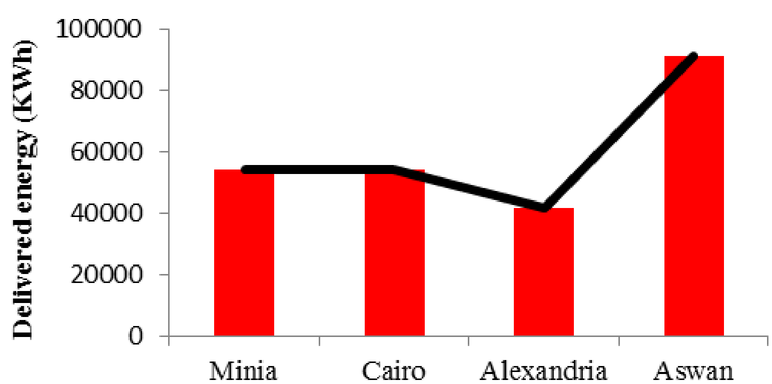


Figure 4-7. Total delivered energy for different locations.

4.4 Summary

The energy consumption of residential buildings represents the majority part of energy usage in Egypt. The results showed that the building orientations mainly lead to reduce cooling demand of building compared with lighting and domestic hot water. The evaluated building's original orientation is to the south-east. Eight orientations are assessed: south (, south-east (base case), east, north-east, north, north-west, west and south-west. The results showed that the optimal orientation was when the building faces North and the worst orientation was when the building faces South. The energy performance of a dwelling in New Minia City, Egypt through different orientations was assessed. The energy consumption of the case study building is 52560 kWh annually. The energy is mostly used for cooling demand by 74.31% of the total delivered energy, the heating demand represented by 12.20% of total energy and the rest of energy demands accounted for 13.34% of total energy. However, this energy demand could be reduced by 5.8% if the building is oriented to the north direction. The difference of the energy consumption between the best and the worst building orientations, North and South, respectively, reached up to 7.5%. The location has even more significant effect on energy consumption up to 42% in the investigated cases.

CHAPTER Five

5. MODEL SIMPLIFICATION ON ENERGY AND COMFORT SIMULATION ANALYSIS FOR RESIDENTIAL BUILDING DESIGN

Different building energy simulation programs are now available, expanding the ability to perform detailed energy evaluations. However, building energy simulation requires a significant amount of resources and time, especially when compared to so-called simplified models. These simplified models often need little input data and are developed with various assumptions about usage patterns, climate, and construction techniques. However, simplified models may also have considerable uncertainty in their results, which may compromise the building energy labeling process.

This chapter evaluates the impact of model simplifications on thermal and visual comfort as well as energy performance. In the framework of dynamic zonal thermal simulation, a case study of a residential building in a hot climate is investigated. A detailed model is created and simplified through four scenarios, by incrementally reducing the number of thermal zones from modeling every space as a separate zone to modeling the building as a single zone. The differences in total energy and comfort performance in the detailed and simplified models are analyzed to evaluate the grade of the simplifications' accuracy

5.1 INTRODUCTION

Existing software needs extensive input and promises excessively high accuracy. Such extreme accuracy and detail are unnecessary and, in fact, impractical at this early stage because details are frequently uncertain and sparse, simulation time is limited, and critical decisions have not yet been made. Despite the proliferation of several building-energy analysis tools in recent years, architects still face difficulties to use the basic tools of energy analysis (Punjabi and Miranda, 2005). The outputs confirmed that the majority of energy simulation tools are not appropriate for the working needs and methods of architects (Attia et al., 2009; Dijk and Luscuere, 2002; Gratia and De Herde, 2002). Usually, simplifications occur during translating real building geometry into an energy simulation model due to the lack of modeler software, or model simplifications serve the reduction of computational effort and calculation time. Though some previous studies such as Liu and Henze (2005), Westphal and Lamberts (2005), and Capozzoli et al. (2009) investigated the effects of simplifications on the energy analysis of buildings, it is often underestimated or neglected. Therefore, it is essential to develop a simplification methodology of building physics modeling tools to reduce the time and costs of thermal and lighting building simulations, without adverse impact on the quality of results. Complex building geometries are often simplified to perform energy performance simulation (Smith et al., 2011). Zhao et al. (2018) identified three common types of geometric model simplifications as follows:

A. Calculating the load for one floor and multiplying it based on the number of floors,
B. (Simplifying the fenestration of modeling (e.g., merging windows in one space's façade),
C. Reducing the number of internal thermal mass and thermal zones of the building.

Despite the valuable results of the previous studies on model simplification, they just evaluate the impact of model simplification on energy simulation in residential buildings or in-office types. The impacts of modeling simplification on the thermal comfort analysis are usually not investigated properly. A study by Korolija and Zehan (2013) analyzed the effect of modeling simplification on thermal comfort analysis, but with a different method and focus as they considered one simplification scenario of treating each floor by a single zone and they assessed the thermal comfort performance through the annual operation of carbon emission and overheating risk. Consequently, it can be stated that there is no study about the effect of model simplifications on thermal and visual comfort published yet.

Important to mention that considering only the energy results during the simplification process is not sufficient to get a truly comparable model version to the original detailed building model, rather it is inevitable to consider all determinate indoor comfort indices as well. Analysis of both comfort and energy results is the only way to identify the optimum model simplification level. The gained thermal zoning simplification method can imply a high design feedback acceleration effect, offering great potential for building design optimization. Geometric modeling is a key step in the process of building energy simulation. However, the geometric modeling process is relatively complex and there is a significant difference between the real model and the building energy model. Therefore, it is usually necessary to simplify the energy model in the geometric modeling stage.

5.2 Materials and methods

5.2.1 Case Study

For the purpose of the model simplifications, a multifamily house as a reference is proposed, representing a generic, typical residential building type in the largest building sector of the world. This reference building model is derived from an existing, common residential house, built-in 2005 in New Minia, Egypt at 30.73 E longitude, 28.08 N latitude (Figure 5-1). The building consists of nine apartments. The ground floor is represented by one apartment and consists of a lounge, dining room, bathroom, and kitchen, with a total floor area of 180 m^2. Each floor of the repeated floors consists of two identical apartments, with 220 m^2 net floor area. Every apartment includes reception, master bedroom, two children's rooms, bathroom, and kitchen as shown in Figure 5-1 and occupied by a couple with two children based on the real evaluation from the field. The composition of building elements was used based on the Egyptian standards, as shown in Table 5-1. IDA ICE has been used to simulate thermal and visual comfort as well as energy performance in a detailed model about the reference building and in several simplification scenarios, whereas the reference model is modified according to the simplification concepts. Table 5-1 presents an overview of the major parameters and input data.

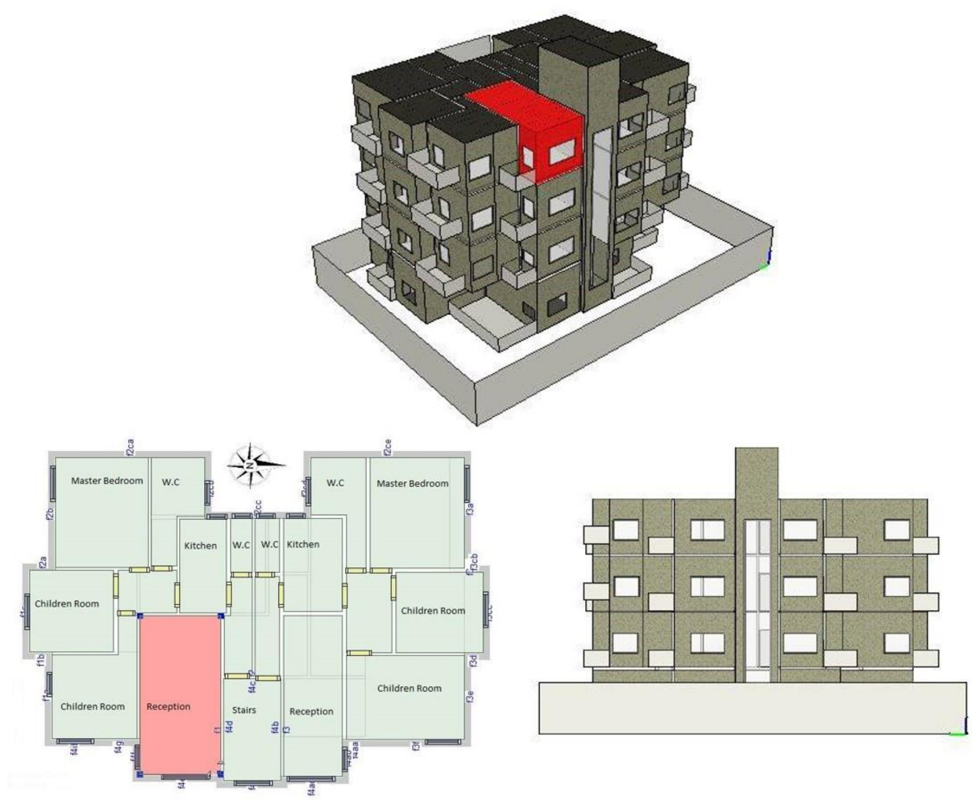


Figure 5-1. Generic residential building as a reference for model simplification tests.

Table 5-1. Boundary conditions for the simulation.

Boundary Conditions	**Model Characteristics**
Location	Minya
Simulation Weather File	EGY_MINYA_623870_IW2.PRN (ASHRAE 2013)
Modeling Software	IDA Indoor Climate and Energy

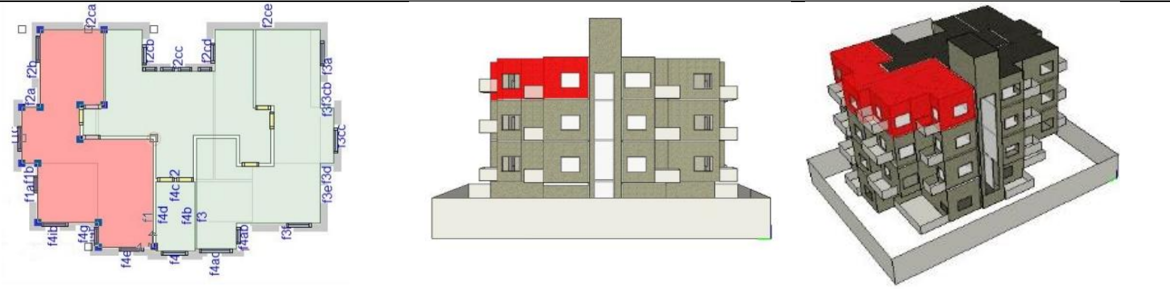
House Type	Family house
Plot Area	300 m^2
Glazing Type	20 mm single glazed glass, U-value=5.9 W/(m^2K)
External Walls	5mm Plaster + 25 mm Egyptian Portland cement mortar+ 250 mm Double red brick +25 mm Egyptian Portland cement mortar + 5 mm Plaster. U-value=1.546 W/(m^2K)
Internal Walls	5 mm plaster + 25 mm Egyptian Portland cement mortar + 125 mm single red brick + 25 mm Egyptian Portland cement mortar + 5 mm plaster U-value=2.281 W/(m^2K)
Internal Floors	10mm concrete tiles + 20 mm Egyptian Portland cement mortar + 50 mm sand + 200 mm plain concrete. U-value = 1.824 W/(m^2K)
Roof	10 mm concrete tiles + 20 mm Egyptian Portland cement mortar+ 50 mm sand +20 mm betomine damp insulation + 150 mm rein force concrete. U-value = 1.707 W/(m^2K)
External Floor	10 mm Concrete tiles+50 mm sand + 20 mm Egyptian Portland cement mortar + 200 mm plain concrete+ 250 mm soil. U-value= 1.172 W/(m^2K)
Basement Wall Towards Ground	5mm Plaster + 25 mm Egyptian Portland cement mortar + 250 mm double red brick + 25 mm Egyptian Portland cement mortar + 5 mm plaster. U-value=1.546 W/(m^2K)
Infiltration	7 ACH
Internal Gains	Occupant: Activity level 1.0 MET Constant clothing 0.85 ±0.25 CLO (clothing is automatically adapted between limits to obtain comfort) Occupancy time: Living room: fully present (1) [7:00-8:00, 17:00-22:00], half present (0.5) [15:00-17:00],0 otherwise, Bedroom 0 [7:00-22:00], 1 otherwise (remaining) Emitted heat per person 75 W Equipment usage time:

	Living room: full intensity 1 [7:00-8:00, 17:00-22:00], half intensity 0.5 [15:00-17:00], Bedroom: 0 [7:00-22:00], 1 otherwise Luminous efficiency 12 lm/W Artificial lighting use: 1- living room From 1 Jan to 14 Apr all days:1 [7:00-8:00, 17:00-22:00],0.5[15-17], 0 otherwise From 16 Oct to 31 Dec all days:1[7:00-8:00, 17:00-22:00] ,0.5[15:00-17:00],0 otherwise From 15 Apr to 15 Oct all days:1 [19:00-22:00], 0 otherwise All days: 0 Bedroom From 1 Jan to 14 Apr all days:1 [6:00-7:00, 22:00-23:00] ,0 otherwise From 16 Oct to 31Dec all days:1 [6:00-7:00,22:00-23:00] ,0 otherwise All days: 0
Schedules	Independ in different spaces
Daylight	Meteonorm database diffuse and direct radiation (W/m^2)
HVAC	No mechanical ventilation. Generic heating and cooling in the zones to compensate heat losses and loads.

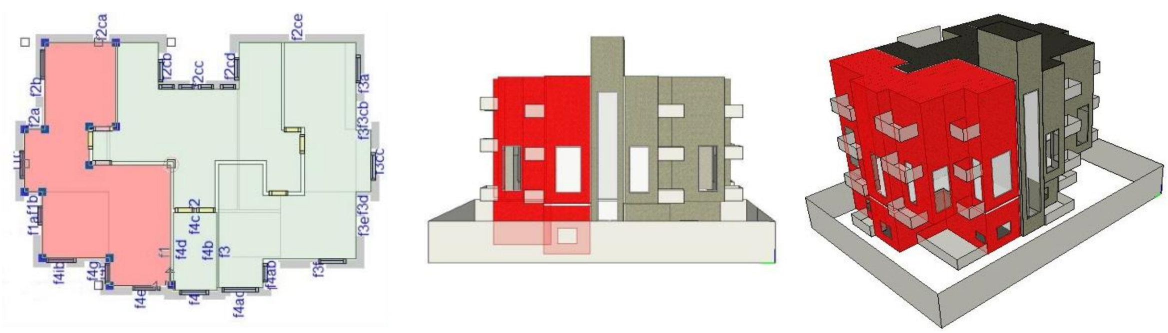
5.2.2 Model Simplification Methodology

This study examines the impact of reducing the number of thermal zones on the prediction accuracy of energy and comfort of residential buildings. A thermal zone represents the division of a dwelling for the convenient calculation of the energy and thermal comfort simulation of the building. The thermal properties and parameters are relatively consistent in the same thermal zone. Obviously, to get more accurate results of energy and thermal comfort, the simulation model should be more accurate regarding the number of modeled thermal zones of the building, but at the same time, it would need more calculation time and, as a result, modeling work expenses. Many countries have provided relevant regulations for the division of thermal zones of the buildings. American National Standards Institute / American Society of Heating, Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE) 90.1 (ASHRAE, 2013) reported that multiple spaces can be represented as one thermal zone with the following requirements: the usage of the spaces and comfort requirements, the air conditioning and heating systems applied in the spaces and the orientation and structural properties of the exterior walls and windows should be the same. The Building Research Establishment Ltd. (2010) stated that a thermal zone is an area that has the same setpoints for cooling and heating, identic operating times of the plant, the same ventilation provisions, and set-back conditions. In addition, they should be served by the same primary plant and terminal device type. The Canadian standard EE4 (2008) stipulates that a thermal zone must have the following features: 1) same air conditioning system and heating with similar operations and functions, and similar heating and cooling loads; 2) the surrounding and the internal space should be distributed into different thermal zones; 3) rooms for laundry, equipment, power distribution, corridors, cloakrooms, and stairs cannot be modeled as a single partition.

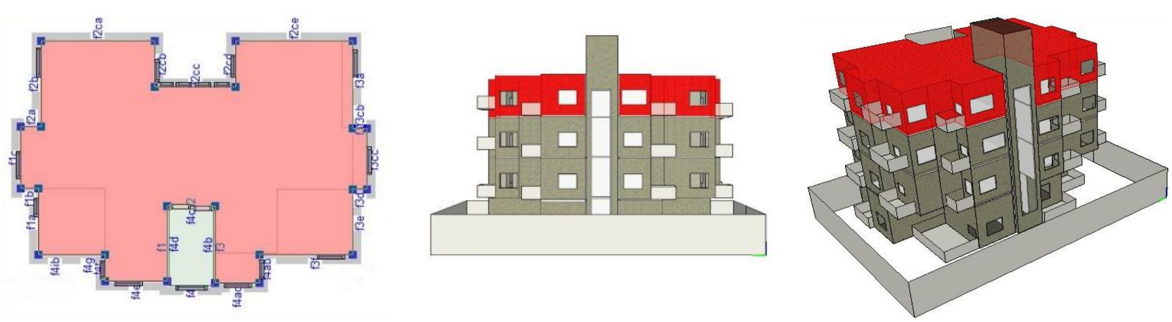
In the following, four different simplification scenarios of the thermal zones are proposed as shown in Figure 5-2 Summary of the simulated scenarios is presented in Table 5-2. First, in the base scenario (BS) model, each space is modeled as a single independent zone (Figure 5-1). Then, scenario S1 combines spaces with similar characteristics (e.g., orientation, operation schedules, same use, etc.) into one thermal zone (Figure 5-2). Then, scenario S2 combines the same oriented spaces for all of the 4 floors into one thermal zone (Figure 5-2). In scenario S3, all spaces on the same floor are merged into one single zone, and scenario S4 models the entire building as one single thermal zone (Figure 5-2).



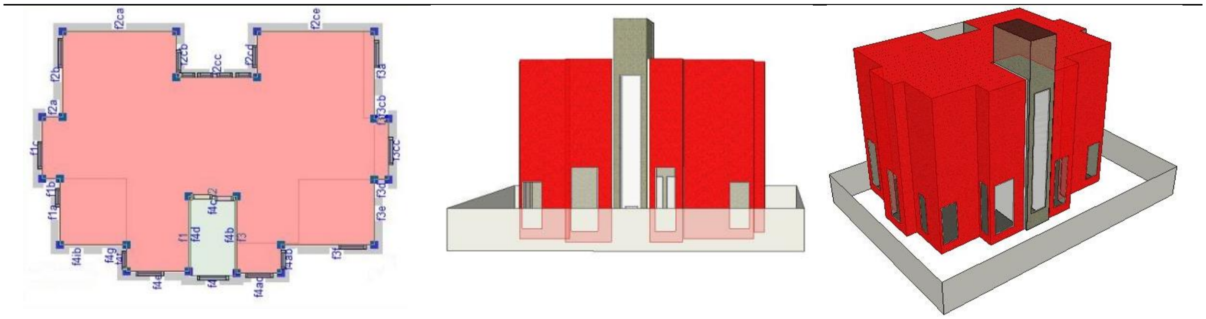
Scenario (S1)



Scenario (S2)



Scenario (S3)



Scenario (S4)

Figure 5-2. Simplification scenarios—simulation models (plan, side, and 3D view).

Table 5-2. Simulated simplification scenarios.

Scenario	Description of Investigated Thermal Zones	Number of Thermal Zones
BS	Base model: Each building space is modeled as a single zone.	64
S1	Floor by floor, all identically oriented spaces with the same function are merged into one zone with the same operation schedules, use, etc.	14
S2	The same oriented spaces with the same use for all of the 4 floors are combined into one thermal zone, i.e., bedrooms on the ground floor, 1st floor, 2nd floor, and 3rd floor are merged with circulation areas into one thermal zone.	8
S3	All rooms on the same floor are merged into one thermal zone, thus in this scenario, the whole building has 4 zones.	4
S4	The entire building is modeled as one single thermal zone.	1

5.3 Results and Discussion

5.3.1 Building energy assessment

IDA ICE has been used to simulate energy consumption and indoor comfort performance of the studied building for the BS model and all the simplification scenarios. Figure 5-3 summarizes the energy results for the BS model and the simplification scenarios in comparison to BS model. The simplification scenarios have a minor effect on the lighting, facility, equipment, tenant, and DHW results due to their similar input parameter and cumulated settings. On the other hand, electric cooling and heating show larger differences. In BS scenario, the cooling demand accounts to 67% of the total energy consumption, while the heating demand attributes to 18%, as the case study is located in a hot and dry climate. Lighting, facility, equipment, tenant and DHW accounted to 15% of the total energy consumption. In S1, the cooling demand increased by 9.6% and the heating demand decreased by 3.1% with respect to BS (Table A1). S2 and S3 scenarios performed an increased cooling demand by 15.1% and 10.6% respectively, while the heating demand decreased by 3.5% and 0.3%, respectively, compared to BS (Table A1). In scenario S4, the heating demand decreased by 23.6% in respect to BS model, while the cooling demand increased by 12.2% compared to BS (Table A1). Similar reports of the simplification on the energy performance are available in the literature, e.g., Heo et al. (2018) and Ren et al. (2019) have reported that merging rooms with similar characteristics into one zone (scenario S1) and modeling a single zone for the entire building (scenario S4) underestimated the annual heating demand by 7% and 24%, respectively, in comparison to modeling every room as a separate zone (detail model) for domestic buildings in the UK. Picco et al. (2014) have also reported that cooling and heating loads were underestimated by 9.29% and 8.12%, respectively for scenario S3 (Every floor was represented by one individual zone) compared to the detailed model in an office building built, located in Bolzano, Italy. Picco and Marengo (2015) have reported similar findings of simplification on cooling and heating demands. They reported that when the number of thermal zones are reduced to one thermal zone per floor (scenario S3), the annual heating and cooling demand are underestimated by 0.86% and 6.25%, respectively. Consistent with the present result, Dipasquale et al. (2013) have also reported that reducing the whole floor to one thermal zone underestimated the annual heating and cooling demand by 12.5% and 22%, respectively with respect to the detailed model. Korolija, and Zhang (2013) have also reported that treating each floor of a house as a single thermal zone underestimated the annual heating demand by 10.6%. The change in the total energy consumption evolved in the first, second, third, and fourth scenarios as follows, +5.8%, +9.5%, +7.1%, +4.0% in respect to the BS model (Table A1). Although the fourth scenario represented the worst scenario considering only the cooling and heating demand individually, it had the smallest change in total energy consumption compared to BS model, because the heating and cooling deviations equaled each other out, resulting in the least difference in total. The thermal envelope is the same in all of the models, hence the fundamental differences can be derived from the complexity level of the actual modeled thermal mass, (walls, slabs) that affect mostly the cooling and heating demand, although the geometrically "missing" thermal mass was added to the model variations as individual mass elements respectively. Case S4's lowest heating demand is caused by the least floor space to be heated.

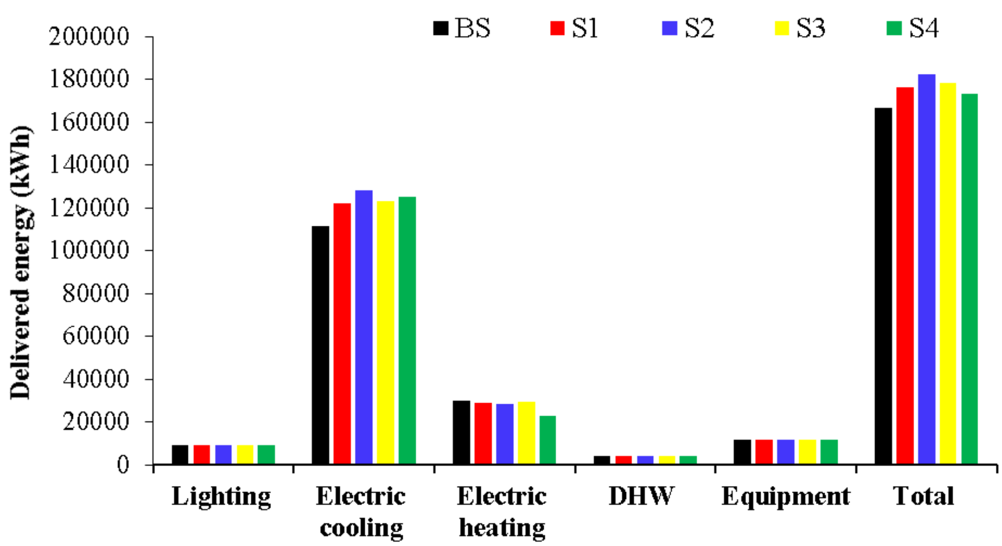


Figure 5-3. Delivered energy for the detailed and simplified models.

5.3.2 Simulation Time and Modeling Time

The total modeling time of the BS model was 215 minutes, while it decreased to 45, 35, 22, and 11 minutes in the simplification scenarios, as shown in Table 5-3. The most decisive difference in modeling expenditure of time takes place in modeling of one story of a building since multifamily houses possess a great diversity of apartment sizes, room arrangements, and room geometries. After completion of a floor, the typically identic domestic levels can be copied above each other to complete the building model; therefore, this modeling work duration is insignificant. As the number of thermal zones are reduced in a story, the simulation time decreases decisively. Considering the geometry and structure creation as well as the editing and parametrization working time, the required modeling time is approx. proportional—with a rate of 1:1—to the number of zones. At the same time, the total simulation time of the BS model was 86 minutes, and it decreased to 32, 14, 23, and 5 minutes in the scenarios. With a decreasing number of thermal zones, the simulation time decreases significantly. The scenarios saved 79 to 95% of the modeling time and 63 to 94% calculation duration compared to BS, demonstrating a huge potential in model simplification and workflow conservation.

Table 5-3. Modeling and calculation duration of the detailed and simplified models and respective differences.

	BS	S1	S2	S3	S4
Modeling time (Minutes)	215	45	35	22	11
Modeling time difference (%)	0	-79	-84	-90	-95
Calculation time (Minutes)	86	32	14	23	5
Calculation time difference (%)	0	-63	-84	-73	-94

5.3.3 Assessment of Building Thermal Comfort

5.3.3.1 Evaluation of Predicted Mean Vote (PMV)

In this study, PMV was evaluated as one of the main indices to assess the thermal comfort in an occupied zone (Ho et al., 2009; Ismail, 2010). Three categories A, B, and C were proposed in ISO 7730, PMV is ranged in the interval of [−0.2, +0.2]; for Category A, in the interval [-0.5, +0.5] for Category B and, in the interval [−0.7, +0.7] for Category C (Carlucci and Pagliano, 2012). Category B represents the normal level of applicability based on ISO 7730. Figure 5-4 shows the average number of annual hours of PMV, category B in the detailed and simplified models' separated as well as merged thermal zones. In the simplified models, the average annual hours of PMV, category B is calculated by an area-weighted averaging of the annual hours of PMV, category B for each thermal zone, as presented in Equation (1)

$$N_{PMV} = \frac{\sum_{i=1}^{i=n} N_i \cdot A_i}{\sum_{i=1}^{i=n} A_i} \qquad (1)$$

where N_{PMV} means the average annual hours of PMV, category B for the whole model, N_i represents the number of annual hours of PMV, category B for thermal zone i, A_i the total area of each thermal zone [m^2], "n" is the total number of thermal zones of the model. For the complete building in BS, the annual hours of PMV, category B were 7781 h, while 6642 were accounted for S1. The annual hours of PMV, category B increased by 6 hours for S2 and, while the annual hours decreased by 875 and 64 hours for S3 models and one-zone model (S4), respectively compared to the BS model, as shown in Table A2. In S2, the difference in the annual hours of PMV, category B increased by 3.2% in the south side and decreased by 29.3% in the north side, related to the BS model (Table A2). Reason for that: in the south-oriented zone, solar gains enabled a higher level of PMV, while in the north zone, the contrary effect evolved, because the high thermal zones (3-story high) are more difficult to heat. In S3, the PMV decreased by 4.7% and 1.7% on the 2nd floor and the 3rd floor respectively, with respect to BS. Reason for that: on the 3rd floor the highest zone is the warmest in summer because of thermal gradient and less thermal mass. However, this greatest deviation is more still at a marginal scale, hence, in general, a consistent calculated thermal comfort sensation was observed in each model.

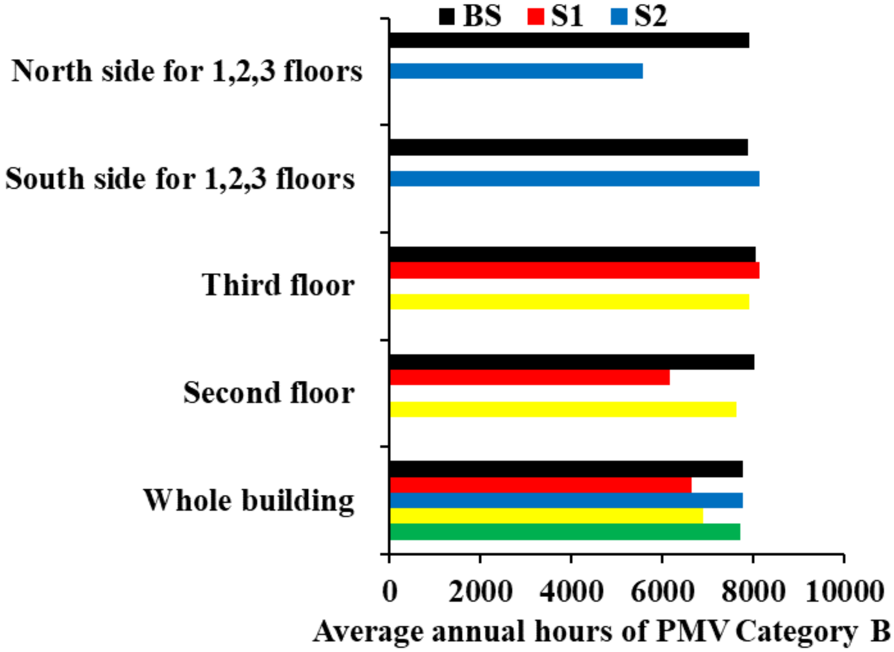


Figure 5-4. Average number of annual hours of PMV, Category B for whole and some parts of the building in the detailed and simplified models.

5.3.3.2 Carbon Dioxide Level Assessment

The concentration of CO_2 was applied as an indicator of indoor air quality (Batog and Badura, 2013). The connection between indoor air quality and indoor CO_2 concentration originates from the fact that at the same time people are generating odor-causing bio effluents and producing CO_2 (Batog and Badura, 2013). In European Standard (CEN-EN 13779, 2007), CO_2 concentration is also applied to classify indoor air quality, and the maximum value of CO_2 concentration level is 1500 ppm, while they recommend keeping CO_2 concentration level below 1000 ppm. In this particular study, the number of annual hours is estimated, when the CO_2 concentration level is above 1000 ppm in the models. The results are compared at three scales (i.e., whole building, 2nd and 3rd floors, south and north sides of the building in all floors).

Figure 5-5 presents the annual hours with CO_2 concentration levels above 1000 ppm in the detailed and simplification models. Additionally, an area weighting such as Equation (1) was used to calculate the average annual hours of CO2 concentration level. Regarding to the complete building, the number of annual hours of CO_2 level above 1000 ppm in BS scenario was 2248 h, while S1 was accounted to 2130 h. In scenarios S2, S3, and S4 this value decreased by 7.2%, 8.4%, and 5.9%, respectively, compared to the BS scenario Table A3. Consistent with the present result, Korolija and Zhang (2013) have also reported that treating each floor of a house as a single thermal zone (scenario S3) underestimated the carbon emission by 8%. In scenarios S1 and S3, the differences in the air quality were 0.1% and 21.7% respectively on the second floor, while 48.9% and 8.7%, differences occurred on the third floor. On the south side of the whole building (S2 – building high thermal zone), the air hygiene decreased by 17.4% at the north side of the building with respect to the BS scenario while the south side accounted to the same hours of BS scenario (Table A3). The merged, simplified zones have more space to be window-ventilated since they include the corridors and secondary spaces (elevator/stairs) as well. That is why they perform higher CO_2 levels. Generally, the distribution of CO_2 concentration shows great inhomogeneity in the different sized thermal zones.

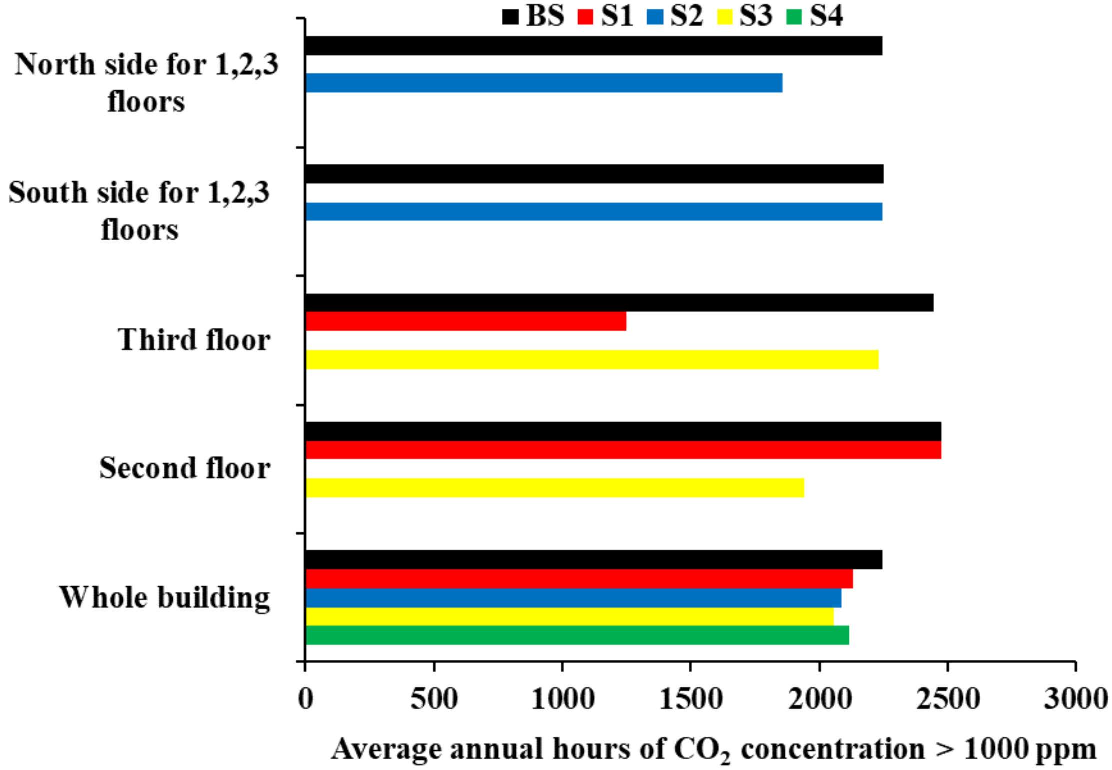


Figure 5-5. Average number of annual hours with CO_2 concentration > 1000 ppm for the whole and some parts of the building in the detailed and simplified models.

5.3.3.3 Daylight Factor Assessment

Daylighting as visual comfort is an effective parameter in sustainable and energy-efficient building design (Ihm et al., 2009) and it is becoming an essential part of the environmentally friendly building design (Kim et al., 2012). Designers and architects should be aware that daylight is a valuable commodity and should take this into account early in the design process. The adequate level of daylight is not only important to illuminate all year long and secondarily to heat in wintertime the interior, but it is also an essential source of the occupant's emotional and physiological well-being. Besides ensuring a low level of odor and noise, daylight provision is an essential parameter in indoor environment investigations for maintaining the enjoyment of a property. Daylighting performance strongly relies on the illuminance under direct, respectively diffuse sky conditions.

Since the daylight provision under direct illuminance (clear sky conditions) in Minia region possesses a high level of daylight autonomy in interior spaces, in this study, the visual comfort assessment focused on the Daylight Factor (DF), representing the illuminance performance of the spaces under mixed sky circumstances, as a kind of 'worst-case scenario'. Satisfying the minimum required DF limit means a whole year-long secured daylighting quality. The DF value is a ratio that represents the amount of illuminance available indoors relative to the illuminance level present outdoors at the same time, under overcast sky (Waldram, 1925). DF at a point of the room is the ratio of the indoor illuminance Ei to the outdoor horizontal illuminance, Eo, (Commission Internationale de l'Eclairage (CIE), 1970), expressed as a percentage in the following Equation (2):

$$\mathrm{DF} = \frac{E_i}{E_o} \text{ x } 100 \ [\%] \tag{2}$$

Calculating Equation (2), the required value of DF for Minia city is 2.1, by applying the required Ei as 300 lx and Eo (median external diffuse illuminance) as 14012 lx according to EN17037 Daylight in Buildings and ASHRAE database. The DF was assessed in all models. Illuminances were computed using meteorological data taken from Meteonorm 7 database (Meteonorm, 2000). Figure 5-6 presents the ratio of floor area performing a DF above (corresponding to adequate daylight space partition) and below (equal to inadequate daylight space partition) the DF (2.1) threshold value. In the case of BS, 21.3% of the floor area is adequate daylight. In S1 and S3, the appropriate daylight floor area increased by 6.1% and 21.6% with respect to BS, while in S2 and S4 delivered significant, 19.8% and 60.3% differences compared to the reference. In S1 the abandonment of all internal walls caused the weaker DF performance and in S3 the additionally merged, deep spaces of the whole story thermal zones indicated the lower level of DF. The reason of the anomalies in S2 and S4 were the different height of the zones in the S2 and S4 models while still referred to the same floor space like in S3.

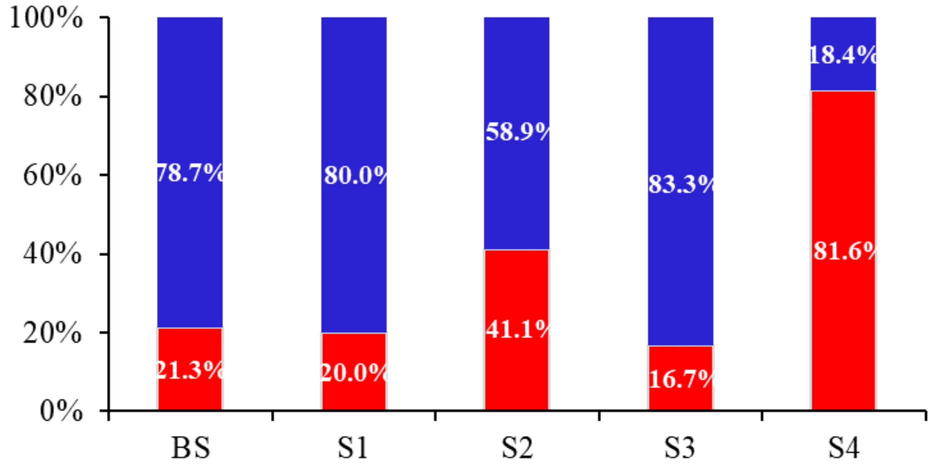


Figure 5-6. Floor area ratio with daylight factor above (red color) and below (blue color) the minimum DF (2.1%) value.

5.3.4 Optimal Scenario of the Proposed Model Simplifications

To determine the optimal scenario of the proposed simplifications, two crucial criteria should be taken into account: the required simulation time and the accuracy of the energy and comfort results. In respect to calculation duration, obviously, the single-zone model (S4) represents the fastest model as shown in Table 5-3, followed by S2 model, S3 model, and S1 model. For the accuracy criteria, Table 5-4 presents the absolute differences of energy demand (heating and cooling) and indoor comfort (PMV, CO_2 level, and DF) in respect to the BS model. More simplification leads to more inaccurate results, as in the S4 model the high differences in energy demand and DF distribution demonstrate. In comparison to BS, (S1) presented the optimal accuracy case of the proposed simplification scenarios, resulting in a 6.8% average difference of all parameters in energy demand and comfort performance. At the same time, S1 saves over 63% of simulation time. S1 is followed by scenarios 3, 2, and 4. Consequently, the model simplification can be accomplished until the anomalies appear due to the simplified geometry.

Table 5-4. Absolute % differences of heating and cooling demand, PMV, CO_2 concentration, and DF between the simplification scenarios and BS.

Parameter	Simplification Scenarios			
	Absolute % Differences with Respect to the BS			
	S1	S2	S3	S4
Heating Demand	3.1	3.5	0.3	23.6
Cooling Demand	9.6	15.1	10.6	12.2
PMV	14.6	0.1	11.3	0.8
CO_2 Concentration	5.3	7.2	8.4	5.9
DF	1.5	20.1	4.5	56.6
Average Differences	6.8	9.2	7.0	19.8
Order	1	3	2	4
% Save in Simulation Time	63	84	73	94

5.4 Conclusions

Accurate building physics performance analysis requires time-consuming, detailed modeling, and calculation time requirements. This chapter evaluates the impact of model simplifications on thermal and visual comfort as well as energy performance for a case study of a residential building in a hot climate using the simulation framework of IDA ICE. The detailed reference building physics simulation model contained all separate rooms modeled as individual thermal zones. A detailed model is simplified through four scenarios, by incrementally reducing the number of thermal zones from modeling every space as a separate zone to modeling the building as a single zone. The interdependency of result accuracy and calculation time proved that the optimal simplification method merges all spaces with similar use and orientation into one-zone floor by floor (scenario S1). Results showed that thermal zone merging as a simulation simplification method has its limitations as well, whereas a too intensive simplification can lead to undesired error rates. It can be concluded that the analysis results will be useful for modelers to determine the optimal level of model simplification in the modeling process depending on the achievable accuracy level of energy performance and thermal comfort.

CHAPTER Six

6. A SENSITIVITY ANALYSIS FOR THERMAL PERFORMANCE OF BUILDING ENVELOPE DESIGN PARAMETERS

Sensitivity analysis is crucial in building energy assessments. It is used to determine the major variables influencing building thermal performance, using both observational research and energy simulation models. Sensitivity analysis is typically performed in conjunction with energy simulations to better understand building performance and minimize consumption. The quality of their outputs is mostly determined by the thermal models and input data. It is challenging to obtain reliable data regarding the attributes and operational status of buildings. As a result, simulation inputs are influenced by uncertainties, which can have a major impact on outcomes and must be considered. Uncertainty analysis considers uncertainties caused by intrinsic model simplifications and a lack of knowledge about input data.

In this chapter, sensitivity analysis is used in conjunction with the IDA-Indoor and Climate Energy (IDA-ICE 4.8) simulation tool to assess the effects of 33 envelope design parameters for energy consumption and carbon dioxide concentrations of a typical residential building in Budapest, Hungary. The results provide an overview of which design factors are most important for enhancing the thermal environment of buildings.

6.1 Introduction

In building energy analysis, sensitivity analysis is an important technique for both observational studies and energy simulation models(Tian, 2013). Sensitivity analysis in the early stages of the design process can provide important information about which design parameters to concentrate on in the subsequent phases of the design.” Sensitivity analysis has the potential to improve the efficiency of the design process and be extremely useful in optimizing building performance." Despite such advancements and efforts, building energy simulation remains a complex process that necessitates and includes modeling and analytical abilities (Claridge and Paulus, 2019). The usage and development of Building Envelope Design Parameters (BEPS) tools, as well as the interpretation of the acquired findings, might be regarded as a problem for building designers and practitioners, who are sometimes unsure about the BEPS tool to be used, as well as the trustworthiness of the associated calculation results (Mahmoud et al., 2020). Uncertainties in the thermal and physical properties of building materials are considered as the main reason for the discrepancy between predicted and actual energy consumption (Elhadad et al., 2019d). The properties vary as a result of (i) degradation over time, (ii) exposure to weather conditions, and (iii) traditional construction processes. Consequently, estimating actual material properties tends to improve the reliability and accuracy of building simulation software. Environmental and energy issues of buildings have recently received significant attention (Hughes et al., 2015; Meng et al., 2020). In addition to the development of green buildings, a large number of existing buildings must also be upgraded to an improved thermal performance level. The primary methods for improving the indoor environment in naturally ventilated residential buildings are envelope and ventilation design. As a result, optimal envelope retrofitting of existing buildings and envelope designs for new residential buildings are urgently required. The effects that design parameters of building envelopes have on energy performance and thermal comfort have been extensively researched. Increasing the insulation thickness can directly enhance the thermal properties of buildings, lowering cooling and heating energy consumption.

The optimal insulation thickness was investigated by Al-Khawaja, Alsayed, and Huang et al. (Al-Khawaja, 2004; Huang et al., 2014; Ucar, 2010). WWR and building shape coefficient (building exterior area/building volume) are critical factors in the design of energy-efficient buildings (Elhadad et al., 2019c; Rais et al., 2020). The lower these factors are, the less heat is lost through the envelope and the less energy is consumed. The preceding study focuses primarily on residential and public buildings. As a result, the most important envelope design parameters differ from those of buildings with active cooling and heating. Uncertainty and sensitivity analysis is an effective tool to identify uncertainties in a system's or simulation tool's input and output (Fuerbringer, 1994; Lomas and Eppel, 1992; Macdonald, 2002). The importance of sensitivity analysis in building energy analysis cannot be overstated. As a result, sensitivity analysis has been widely used to investigate building thermal performance characteristics in a variety of applications, including building design (Hopfe and Hensen, 2011; Hygh et al., 2012), energy model calibration (Sun and Reddy, 2006; Westphal and Lamberts, 2005), building stock (Gustafsson, 1998; Lam et al., 2008), building retrofit and refurbishment (Moran et al., 2012; Tian and Choudhary, 2012), and the effect of climate change on thermal performance buildings (P. de Wilde and Tian, 2009; Wei Tian and de Wilde, 2011). Furthermore, practitioners of building energy modeling have shown a rising interest in uncertainty and sensitivity analysis approaches in recent years. From the perspective of a building energy retrofit, uncertainty analysis and sensitivity analysis are often used to evaluate the risk of various energy-saving methods and to aid decision-making.

6.2 Materials and Methods

6.2.1 Study Area

For the purpose of the sensitivity analysis, the family building is proposed, representing a typical residential building type in the world's largest building sector. This reference building is a two-story floor (Figure 6-1). The ground floor area consists of 14 zones with a total area of 200 m^2 with a ceiling height of 2.8 m, 4 zones are distributed on the first floor the first-floor area is 187 m^2 with a ceiling height of 2.6 m.

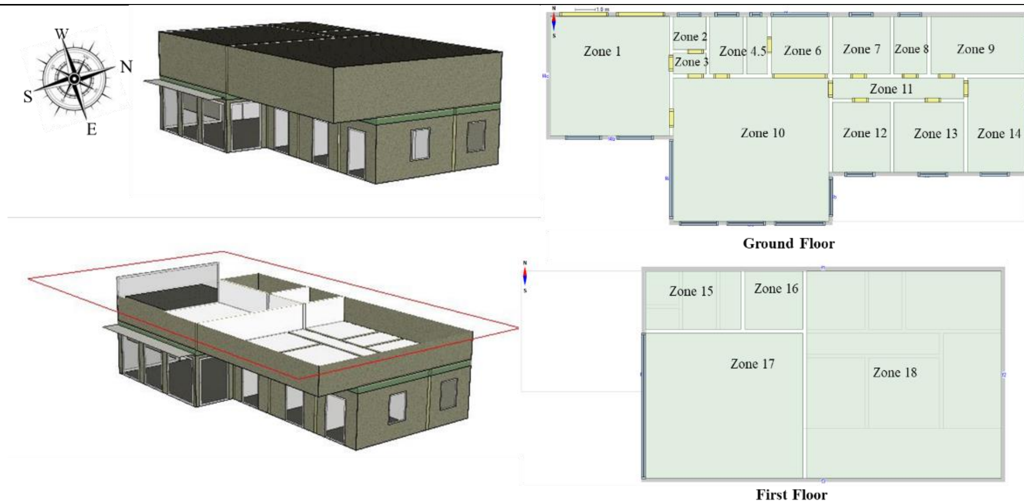


Figure 6-1. IDA-ICE model of the case study.

IDA-ICE was utilized as a reliable tool to simulate the building's energy and thermal comfort performance providing a comprehensive model and sensitivity analysis (Elhadad et al., 2018). Table 6-1and Table 6-2 summarize the used materials in the construction of this building and input data. The schedules for occupants and lighting were created based on the assumption of regular daily patterns. Occupancy and lighting schedules on weekdays and weekend for different thermal zones are defined in IDA-ICE as shown in Figure 6-2. The properties of thermal zones in the investigated building are presented in Table A4. The internal emitted heat per person was assumed to be 75 W when present. Constant clothing level was set 0.85 ± 0.25 CLO (clothing is automatically adapted between limits to obtain comfort). Ventilation air change rate and air pressure difference are set by 0.5 ACH and 50 Pa, respectively. No integrated window shading was used in this building.

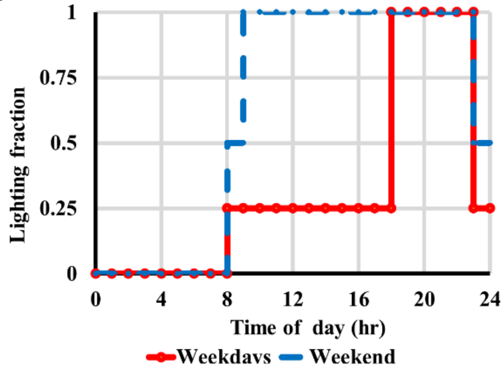
Table 6-1. The used materials in the construction of the investigated building (reference case).

Component	Material	Thickness (m)	Conductivity (W/m K)	Density (kg/m^3)	Specific Heat (J/(kg K)	U-Value
Exterior Wall	Gypsum	5.0E-4	0.29	800	840	0.4518
	Plasterboards	0.02	0.24	1000	840	
	Air gap	0.05	0.17	1.2	1006	
	Brick	0.11	0.58	1500	840	

	Baumit noble plaster	0.002	0.93	1500	880	
	Plasterboard	0.015	0.24	1000	840	
Interior Wall	Brick	0.16	0.58	1500	840	1.752
	Plasterboard	0.19	0.24	1000	840	
Door	Wood	0.05	0.14	500	2300	1.897
	Floor coating	0.02	0.18	1100	920	
Internal Floors	L/W concrete	0.06	0.15	500	1050	0.32
	heavy insulation	0.04	0.052	92	982	
	concrete	0.2	1.7	2300	880	
Roof	Light insulation	0.2	0.036	20	750	0.172
	concrete	0.15	1.7	2300	880	
External Floor	Floor coating	0.005	0.18	1100	920	2.9
	concrete	0.25	1.7	2300	880	
Basement wall towards Ground	Render	0.01	0.8	1800	790	3.332
	Concrete	0.2	1.7	2300	880	
Slab on ground	Plasterboard	0.064	0.4	1250	840	1.12
	Air in 30 mm vert.air gap	0.3	0.17	1.2	1006	
	Plasterboard	0.02	0.4	1250	840	
	reinforced concrete screed	0.0155	1.55	2400	840	
	gravel	0.5	0.35	1800	840	

Table 6-2. Glass parameters.

	Solar Heat Gain Coefficient (SHGC)	**T, Solar Transmittance**	**Tvis, Visible Transmittance**	**Glazing U-Value W/m2K**	**Internal Emissivity**	**External Emissivity**
Glass	0.52	0.50	0.71	0.80	0.837	0.837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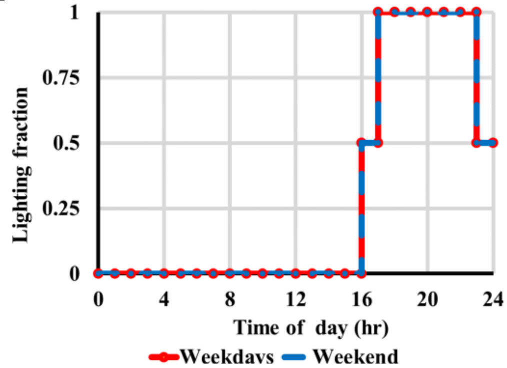
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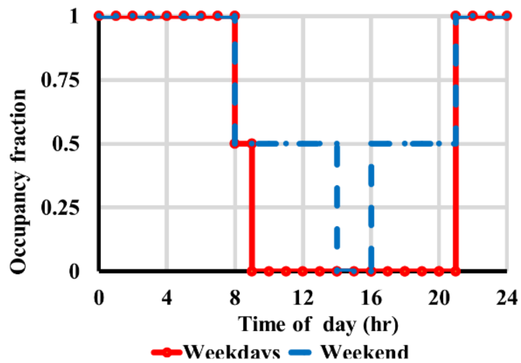
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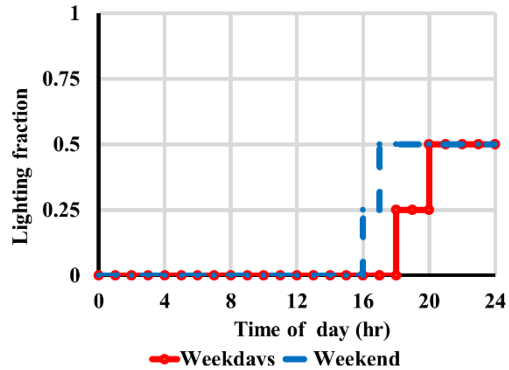
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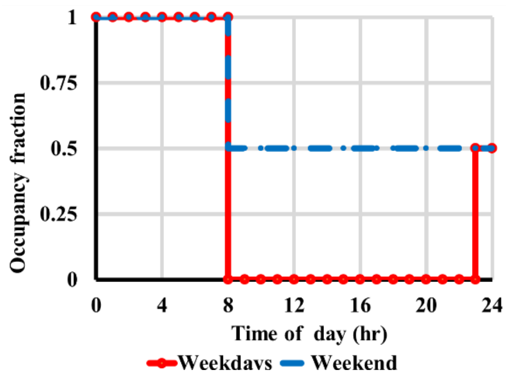
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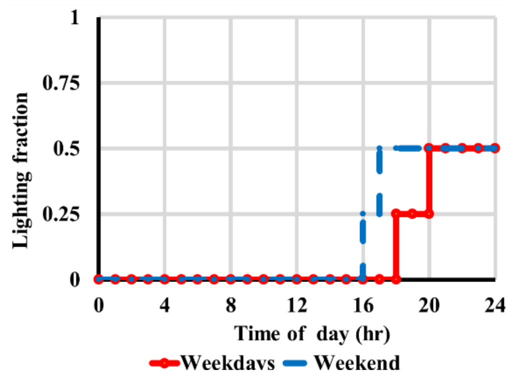
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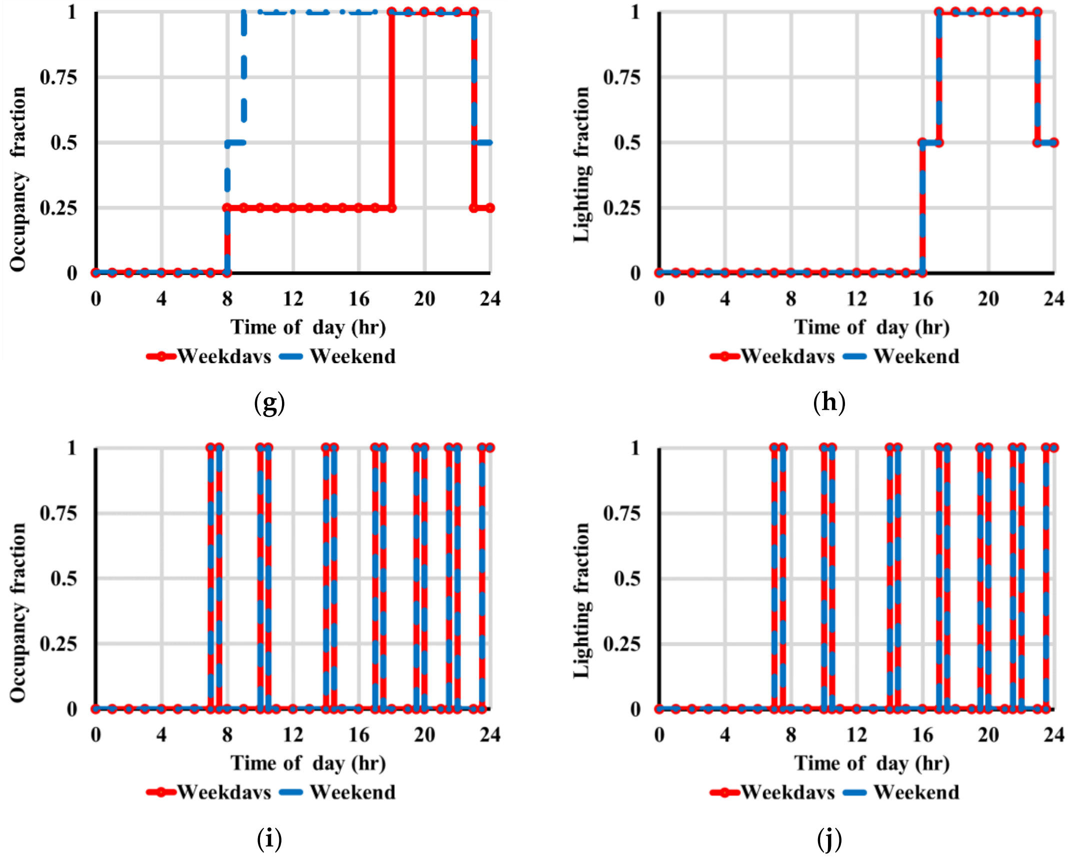

Figure 6-2. Occupancy and lighting schedules on weekdays and weekend for different thermal zones (a,b) living room; (c,d) bedroom; (e,f) children room; (g,h) kitchen; and (i,j) toilet.

6.2.2 Sensitivity Analysis

To gain a better knowledge of the building's performance, sensitivity analysis was used to identify the relationship between independent and dependent factors. Sensitivity analysis is utilized in building design, retrofitting, stock management, and assessing the impact of climate change on structures (see (P. de Wilde and Tian, 2009; Elhadad et al., 2018; Heo et al., 2015; Hopfe and Hensen, 2011; Moran et al., 2012; Song et al., 2014; Sun and Reddy, 2006). Sensitivity analysis and simulation tools can be used in tandem to help conclude better design decisions (Attia et al., 2012). They can be applied to define the key variables influencing building thermal performance based on both observational studies and energy simulation models. Sensitivity analysis is defined as a measure of the impact of a given input on the output (Saltelli et al., 2002). It can quantitatively examine the impact of each parameter of a building envelope and define important design parameters for reducing energy consumption and improving the thermal environment. In this paper, a sensitivity analysis method was used. Sensitivity analysis is frequently quantified in building research as the difference in simulated results caused by changes in input parameters. It gives designers a reliable tool for quantifying the impact of various design parameters and identifying sources of uncertainty. It has also been applied widely in building energy analysis as it not only prioritizes energy-saving solutions but also analyzes energy-use patterns for energy optimization and model calibration (Tian, 2013; Tian et al., 2016, 2014).

The sensitivity methods utilized in building performance analysis may be classified into two types: global and local sensitivity analysis approaches (Tian, 2013). Global techniques are increasingly used in research because they consider the consequences of uncertain inputs over the whole input space (Mara and Tarantola, 2008) which allows for a more complete examination of the link between inputs and outputs throughout the whole input space. This, in return, results in more dependable energy-saving solutions. The downsides of utilizing global techniques are that they are more computationally intensive than local sensitivity analyses. Global sensitivity analyses can be further classified into the following approaches: Morris design, screening-based methods (Corrado and Mechri, 2009; de Wit and Augenbroe, 2002; Garcia Sanchez et al., 2014; Heiselberg et al., 2009; Heo et al., 2012; Hyeun Jun Moon, 2010; Hyun et al., 2008), variance-based methods (Garcia Sanchez et al., 2014; Hyun et al., 2008; Mechri et al., 2010; Ruiz et al., 2012; Shen and Tzempelikos, 2013), regression methods (Ballarini and Corrado, 2012; Breesch and Janssens, 2010; Brohus et al., 2009; Pieter de Wilde and Tian, 2009; Domínguez-Muñoz et al., 2010; Hopfe and Hensen, 2011; Moran et al., 2012; Struck et al., 2009; W. Tian and de Wilde, 2011; Wright et al., 2012; Yildiz et al., 2012; Zhao, 2012; Zhao et al., 2012), and meta-modeling approaches (de Wilde and Tian, 2010; Wei Tian and de Wilde, 2011; Westphal and Lamberts, 2005). Local sensitivity analysis techniques, on the other hand, can only investigate the connection between the data points utilized in the analysis without taking into account interactions among inputs (Saltelli et al., 2008). They are mainly concerned with the impacts of uncertain inputs at a point (or base case).

This section describes how different model parameters entered influence variations in model output by using a number of estimators relevant for individual parameters. The effect of a parameter is determined by changing input and analyzing changes in output. It can be applied to determine the extent to which each input parameter contributes to the generation of output variability and to define the most significant parameters. The sensitivity coefficient Sm of the design parameter m can be determined as (Chow and Chan, 1995; Meng et al., 2020).

$$Sm = \frac{(\Delta X/Xn)}{(\Delta Ym/Ym,n)} \times 100\% \tag{1}$$

where ΔYm is the change in the value of input parameter m, ΔYm = Ym − Ym, n; Ym is the value of the input parameter m; Ym, n is the value of the input parameter m as a baseline value; ΔX is the output variation for the change in the input parameter, ΔX = Xm − Xn; Xm is the output value corresponding to the input value Ym; and Xn is the output value in the baseline case.

Sensitivity analysis can help to improve the efficiency of the design process and optimize the envelope of a building (Heiselberg et al., 2009). The structure of sensitivity analysis is presented in Figure 6-3. The four basic steps for sensitivity analysis are:

- Specify the input and output variables, as well as the interval and range of each input parameter;
- Assign the baseline design parameters and compute the output of the baseline case;
- Compute the output distribution due to the variations of a given input parameter, and compute the sensitivity coefficient using Equation (1); and
- Evaluate the impact and significance of each design parameter on the output variables.

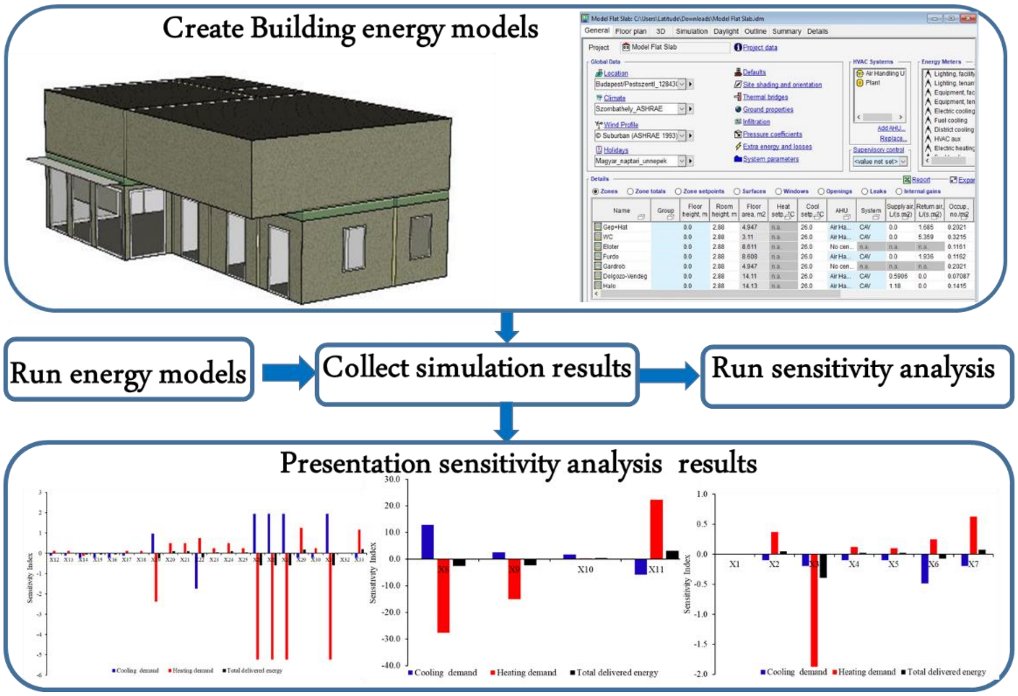

Figure 6-3. Structure of methodology.

6.2.2.1 Input Parameters

Before conducting sensitivity analysis, it is critical to define which input parameters will be examined. To determine this a literature study (Brohus et al., 2012; de Wilde and Tian, 2010; Macdonald and Strachan, 2001; Reddy et al., 2006) was conducted which allowed information regarding distributions utilized for each input parameter type to be obtained. Such uncertainties influence a total of 33 input parameters. As input parameters, 33 envelope design parameters were chosen (exterior floor type, exterior wall type, interior wall type, glazing type, infiltration rate type, thickness, density, specific heat, and thermal conductivity for basement, exterior floor, interior floor, exterior wall, interior wall, roof, and ground slab). Table 6-3 presents parameters and parameter ranges used in the sensitivity analysis. Different materials for the exterior floor, exterior wall, and interior wall were applied. Density, specific heat, and thermal conductivity for concrete range from 2100 to 2500 kg/m^3, 672 to 1050 J/kg K, and 1.07 to 1.7 W/mK, respectively, while ranges 1500 to 1800 kg/m^3, 800 to 840

J/kg K, and 0.58 to 0.73 W/mK correspond to the brick. Four different types of glazing were selected. Infiltration flowrate ranged from 0.2 to 2 m^3/s. The thickness range for the building envelope is presented in Table 6-3.

Table 6-3. Parameters and parameter ranges used in the sensitivity analysis.

	Description of Parameters	**Name**	**Range ***	**Type**	**Distribution**
Thickness	Basement	X1	0.21–0.30	Continues	Uniform
(m)	Exterior floor	X2	0.20–0.30	Continues	Uniform
	Interior floor	X3	0.15–0.25	Continues	Uniform
	Exterior wall	X4	0.15–0.25	Continues	Uniform
	Interior wal	X5	0.11–0.20	Continues	Uniform
	Roof	X6	0.20–0.35	Continues	Uniform
	Ground slab	X7	0.12–0.25	Continues	Uniform
Material	Exterior floor	X8	100, 101, …, 103	Discrete	Uniform
	Exterior wall	X9	200, 201, …, 205	Discrete	Uniform
	Interior wall	X10	300, 301, …, 303	Discrete	Uniform
	Glazing type	X11	400, 401, …, 404	Discrete	Uniform
Density	Basement	X12	2100–2500	Continues	Uniform
(kg/m^3)	Exterior floor	X13	2100–2500	Continues	Uniform
	Interior floor	X14	2100–2500	Continues	Uniform
	Exterior wall	X15	1500–1800	Continues	Uniform
	Interior wall	X16	1500–1800	Continues	Uniform

	Roof	X17	2100–2500	Continues	Uniform
	Ground slab	X18	2100–2500	Continues	Uniform
Specific heat	Basement	X19	672–880	Continues	Uniform
((J/kg K)	Exterior floor	X20	672–880	Continues	Uniform
	Interior floor	X21	672–1050	Continues	Uniform
	Exterior wall	X22	800–840	Continues	Uniform
	Interior wall	X23	800–840	Continues	Uniform
	Roof	X24	672–880	Continues	Uniform
	Ground slab	X25	672–840	Continues	Uniform
Thermal conductivity	Basement	X26	1.07–1.7	Continues	Uniform
(W/mK)	Exterior floor	X27	1.07–1.7	Continues	Uniform
	Interior floor	X28	1.07–1.7	Continues	Uniform
	Exterior wall	X29	0.58–0.73	Continues	Uniform
	Interior wall	X30	0.58–0.73	Continues	Uniform
	Roof	X31	1.07–1.7	Continues	Uniform
	Ground slab	X32	1.07–1.7	Continues	Uniform
Infiltration rate (m^3/s)	Infiltration rate	X33	0.2–2.0	Continues	Uniform

* For discrete parameters, each number in IDA-ICE represents a codified name of a building element (e.g., 101 indicates “Exterior floor-joist floor against”).

6.2.2.2 Output Variables

The output variables included the assessment of energy consumption and indoor thermal comfort performance. The delivered energy for heating and cooling, lighting, equipment, appliances, and DHW are investigated. CO_2 concentrations were assessed as one of the main indices to evaluate thermal comfort.

6.3 Results and discussion

6.3.1 Sensitivity Analysis for the Energy Assessment

The goal of the research was to address some of the concerns discovered in existing literature analysis and case study into input parameters and evaluate what kind of influence these issues have on energy consumption and thermal comfort. Although the sensitivity analysis results cannot be applied to all structures, the study demonstrates that different input factors have variable effects on the building's thermal performance. As a result, the study reaffirms the necessity for participants to be more strategic in determining where to place their emphasis when collecting field data, conducting tests, and modeling buildings. The input parameters are divided into three groups: thickness change parameters; materials change parameters; density-specific heat and thermal conductivity parameters while other relevant parameters, such as building geometry, occupancy schedules, temperature setpoints, air change rates, and natural ventilation are assumed to be constant. Thus, the generated findings cannot be generalized to all dwellings, which may diminish the likelihood of our findings in different types of dwellings.

The results demonstrate that only heating and cooling demand varies with the different runs of sensitivity analysis with very little variation in energy demand for illumination, facility, equipment, tenant, and DHW. Figure 6-4 shows the mean sensitivity coefficient for each change in the thickness parameter for heating demand, cooling demand, and total delivered energy. The sensitivity coefficients of interior floor thickness (X3) represent the highest value of 1.9% and 0.2% for cooling and total delivered energy, respectively, while the basement thickness (X1) has the lowest sensitivity coefficient value for cooling, heating, and total energy. The thickness of the interior floor and interior wall also have minimal impact on delivered energy.

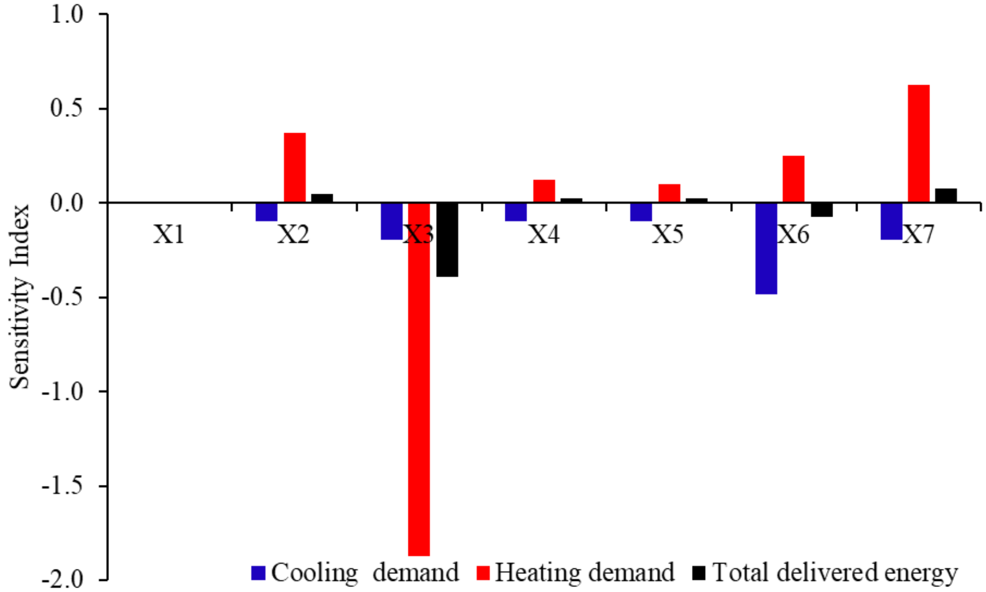

Figure 6-4. Sensitivity coefficient of thickness change parameters.

Figure 6-5 presents the mean sensitivity coefficient of material change design parameters. With respect to material change design parameters, the weights of exterior floor material (X8) are 27.7% and 12.8% for heating and cooling demand, respectively. The exterior floor material of the roof also plays an important role in delivered energy. The sensitivity coefficient of the glazing type (X11) is 22.3% and 5.9%, and the sensitivity coefficient of the exterior wall material (X9) is 15.1% and 2.6% for heating and cooling demand, respectively. On the other hand, the internal wall materials (X10) have a minimal effect on the energy demand for cooling and heating with a sensitivity coefficient of 0.2% and 1.7%, respectively.

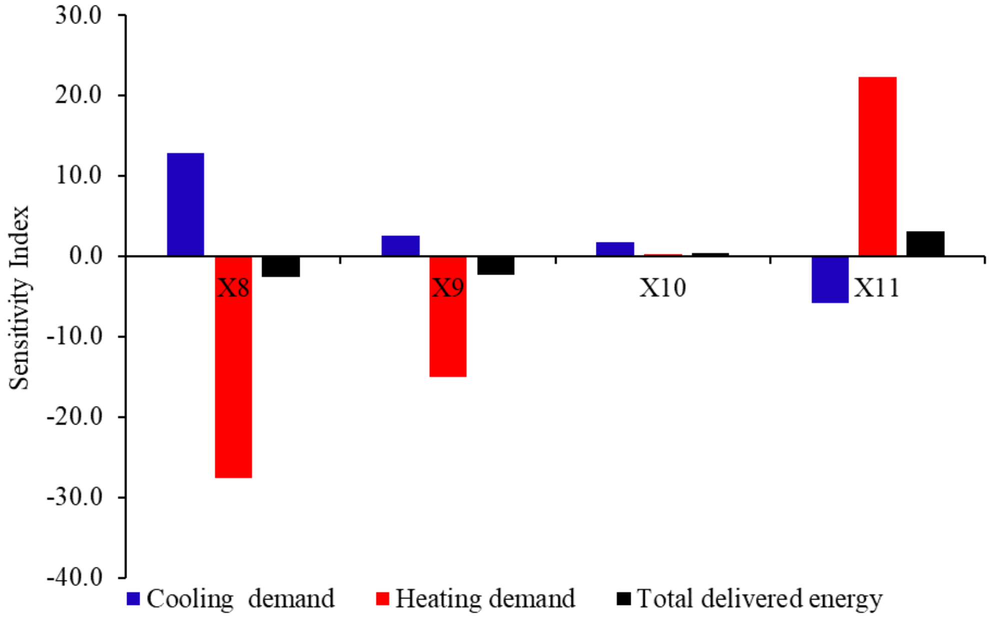

Figure 6-5. Sensitivity coefficient for different materials.

The mean sensitivity coefficient of density, specific heat, thermal conductivity, and the infiltration rate design parameter for heating demand, cooling demand, and total delivered energy are shown in Figure 6-6. The sensitivity analysis reveals that the density of the basement wall, exterior floor and wall, interior floor and wall, roof, and ground slab, (X12–X18); all have a minimal effect on electric heating demand and cooling demand and total delivered energy. Thermal conductivity of the basement wall, interior floor, exterior floor materials (X26–X28) have the greatest impact on heating and cooling demand with sensitivity coefficients of 5.24%, 1.95%, and 0.59%, respectively. The thermal conductivity sensitivity coefficient of the roof (X31) and the exterior wall (X29) are 5.2% and 1.2%, respectively, for the heating demand. The sensitivity coefficient of the basement specific heat (X19), exterior and interior specific heat (X20–X21) are 2.4% and 0.5%, respectively, while the sensitivity coefficient of the exterior wall specific heat is 1.7% for cooling demand.

Figure 6-4, Figure 6-5, and Figure 6-6 depict that changes to the material parameters have the most obvious effect on total delivered energy. The impact of thermal conductivity parameters is the second most sensitive category, followed by the specific heat design parameters in the third group and thickness change design parameters in the fourth group. Finally, the density of all structural materials comes in the least sensitive category. This study provides an overview of which design factors are most important for enhancing the thermal environment of buildings. Given the limited time available for energy modelers to construct energy models, the emphasis should be on ensuring that the inputs having the greatest influence are tailored to properly represent the existing building circumstances.

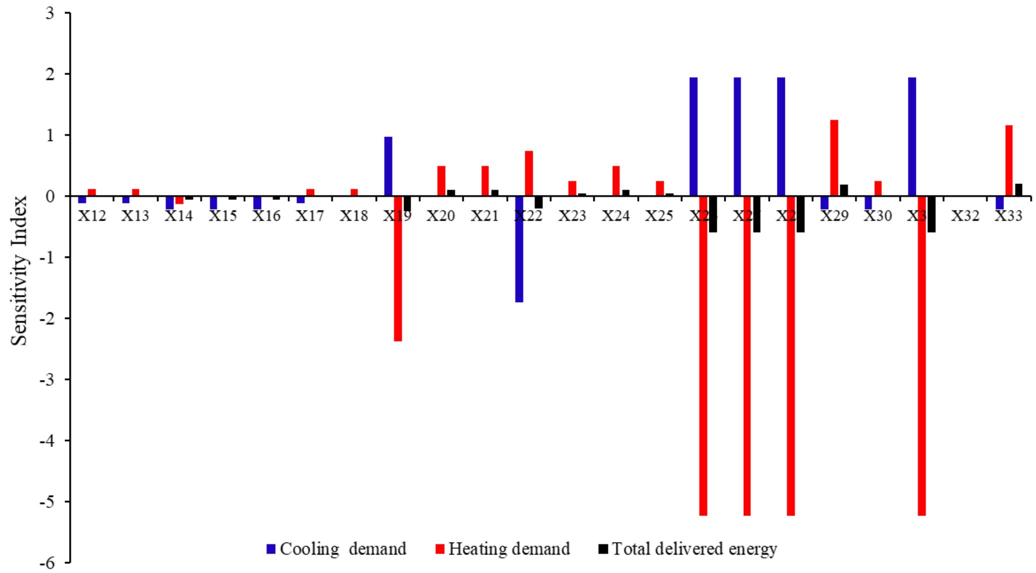

Figure 6-6. Sensitivity coefficient of density, specific heat, and thermal conductivity parameters.

The findings are especially intriguing since the input factors that had the greatest influence on energy analysis results corresponded to current building information, occupancy schedules, and thermostat settings, which industry observers could easily record during an energy audit. Because these characteristics are generally constant before and after the retrofit, more accurate modeling would be possible. Moreover, the results can assist designers in the early stages of envelope design of newly constructed buildings, as well as envelope rehabilitation of existing buildings.

6.3.2 Sensitivity Analysis on Carbon Dioxide (CO_2) Concentrations

Carbon dioxide concentration is used as an indication of indoor air quality (Batog and Badura, 2013). The link between indoor air quality and indoor CO_2 concentrations stems from the idea that individuals produce bio effluents odors while also creating CO_2 (Batog and Badura, 2013). CO_2 concentration is also used to classify indoor air quality in European Standard EN 13779 and the highest value of CO_2 concentration is 1500 ppm, although it is recommended to keep CO_2 concentrations below 1000 ppm. In this study, The findings demonstrate that CO_2 concentrations were comparatively low with an average value around 651.5 ppm for all scenarios due to more frequent window openings and a higher air exchange rate, resulting in better air quality. Thus, none of the selected design parameters were affected by carbon dioxide levels. Moreover, CO_2 concentrations are mainly affected by other variables such as occupancy schedules and air change rates which are assumed to be constant in the current study. Future studies might involve expanding the analysis to include those parameters.

6.4 Summary

This chapter discussed the possible use of sensitivity analysis in the field of buildings' thermal performance analysis and demonstrated its practical application via a case study. The sensitivity coefficient of 33 envelope design parameters for delivered energy and thermal comfort were calculated and compared for a residential building. The most critical design parameters were identified for the analyzed building. The results showed that the material of the exterior floor had the most significant impact on the delivered energy of the building. All envelope design parameters had minimal impact on carbon concentrations. This study provides an overview of which design factors are most important for enhancing the thermal environment of buildings.

CHAPTER Seven

7. CONCLUSION AND FUTURE WORK

7.1 Introduction

The detailed conclusions have been recorded at the end of each chapter of the research. Conclusions based on the studies presented in the preceding chapters will be outlined. The recommendations for future works are given at the end of the chapter.

7.2 Main Conclusion

There were four main parts of this study: The first part presents approaches to explore reducing energy consumption and increasing thermal comfort performance for a residential building in New Minia, Egypt through investigating different passive strategies. The different scenarios of passive strategies include thermal insulation, fixed shading, infiltration, the number of glazing panes are simulated by computational IDA ICE 4.7. The second part is to analyze and quantify the importance of the building orientation to provide appropriate thermal comfort and high energy performance for the building that lead to reduce the energy consumption of the dwelling. Also, study the impact of the location of the building, especially when the latitude and weather are different through (Cairo, Aswan, and Alexandria) on energy consumption.

The third part covers the effects of the model simplification methods on energy consumption, CO_2 level, PMV, and DF performance in a common residential building in New Minia, Egypt. The detailed reference building physics simulation model contained all separate rooms modeled as individual thermal zones. The model was then simplified in scenario S1, whereas all spaces with similar use and orientation were merged into one-zone floor by floor. The same oriented spaces for all of the 4 floors were combined into one thermal zone in scenario S2. Every floor was represented by one individual zone in scenario S3, and the whole building was treated as one single zone for scenario S4. The simplification approach is carried out in the simulation framework of IDA ICE.

The fourth part discussed the possible use of sensitivity analysis in the field of buildings' thermal performance analysis and demonstrated its practical application via a case study. Sensitivity analysis is used in conjunction with the IDA-Indoor and Climate Energy (IDA-ICE 4.8) simulation. The sensitivity coefficient of 33 envelope design parameters for delivered energy and thermal comfort were calculated and compared for buildings in Budapest, Hungary. The input parameters included the thickness, materials, density, specific heat, and thermal conductivity of the basement, exterior floor, interior floor, exterior wall, interior wall, roof, and ground slab, glazing type, and infiltration rate. The most critical design parameters were identified for the analyzed building.

. **The primary findings of this thesis are as follows:**

- For passive design strategies

Passive design strategies can reduce the load of active systems if they are utilized properly. Buildings should be built to offer appropriate natural lighting and ventilation while also allowing building users to manage these variables. It is critical in passive cooling design that all major parts of the structure either block or reject solar heat gain to keep the building cool during the summer heat. Passive design is influenced by the climatic conditions of the place and should be planned accordingly. Most of the energy load in a hot and arid region comes from mechanical systems, thus this load might be lowered by adding features to the building, such as orientation, thermal insulation, the number of glazing panes , infiltration, and fixed shading. The simulation results were analyzed and showed the potential for energy savings and ideal thermal comfort if passive cooling measures were implemented. All of the temperatures attained with the use of passive cooling solutions were within Egypt's comfort zone. Furthermore, employing more passive solutions can considerably improve building thermal comfort even in extreme weather situations The results show that the most effective passive strategies were thermal insulation and increasing the number of glazing panes. On the other hand, infiltration represents the least effective passive strategy, thus, it is not recommended to achieve an air-tight building for building a hot and arid climate. Combining several of these measures can dramatically enhance building energy performance and air quality, resulting in additional financial benefits. To be more useful and competitive to the high-cost mechanical and electrical cooling systems, modern living necessities required some management of these passive techniques.

- For the effect of building orientation

The building orientation has a noticeable effect on reducing the energy consumption of the building. The best building orientation can save up to 6.7% in cooling and 5.8% of total energy demand compared with the existing investigated orientation. Indeed, the difference in energy consumption between the best and the worse orientations can reach 7.8% in cooling and 7.5 % of total energy demand.

- For model simplification:

A model simplification method that merges all spaces with similar use and orientation into one-zone floor by floor (scenario S1), enables the shortening of the required modeling time of 79% and the acceleration of the required solver calculation duration by 63%. At the same time, the comfort performance values possess 21.4% deviations, while the energy performance results are underestimated by 12.7% in comparison to the detailed model. Combining the same oriented spaces with the same use for all of the 4 floors into one thermal zone (scenarios S2) reduces the simulation time by 84%, while the deviation in total energy demand and thermal comfort are 18.6% and 27.4%, respectively, compared to the detailed model. When the number of thermal zones is further reduced to one thermal zone per floor (scenarios S3), the simulation time is saved by 73%, while the energy and thermal comfort are underestimated by 10.9% and 24.2%. However, modeling the entire building by a single zone (scenarios S4) saves 95% and 94% of the required modeling time and the simulation time, respectively, the energy and thermal comfort are underestimated by 35.8% and 63.3%, respectively. The interdependency of result accuracy and calculation time proved that the optimal simplification method merges all spaces with similar use and orientation into one-zone floor by floor (scenario S1). It is obvious that besides the advantages the geometrical simplifications might carry some limitations as well. Results showed that thermal zone merging as a simulation simplification method has its limitations as well, whereas a too intensive simplification can lead to undesired error rates. Furthermore, the essentially geometry related daylight distribution interpretation can be affected due to the different depth of the merged zones. In addition, the orientation should be considered with consciousness, since the different oriented zones should not be combined to avoid different solar heat load (summer) or heat gain (winter) effects to be mixed in one greater unified zone to confuse both energy and comfort behavior. The analysis results will be useful for modelers to determine the optimal level of model simplification in the modeling process depending on the achievable accuracy level of energy performance and thermal comfort. The method provided promising results for further applications and it is intended to be further tested in next multifamily projects and office buildings to prove its reliability in building industry standard practice.

- For the sensitivity analysis of buildings thermal performance

The results showed that the material of the exterior floor had the most significant impact on the delivered energy of the building. The parameter's influence in terms of weights were 27.7%, 12.8%, and 2.6% for heating demand, cooling demand, and total delivered energy, respectively. The second most influencing factors were the thermal conductivity parameters. The impact of the density of all structural elements and the thickness of the basement floor, exterior floor, interior floor, and wall had the least impact on total delivered energy. All envelope design parameters had minimal impact on carbon concentrations. This study provides an overview of which design factors are most important for enhancing the thermal environment of buildings. These findings were interesting since not only did these misrepresented inputs have the greatest influence of those examined, but much of the input parameter data would be very straightforward to collect through a site visit, tests, and interviews with the building inhabitants. Moreover, they can assist designers in the early stages of envelope design for newly constructed buildings, as well as envelope rehabilitation of existing buildings

7.3 Recommendations for Future Works

Further research is needed to enhance the approach in light of the issues identified in this study, which include, but are not limited to:

- Further study is required to investigate the impact on reducing energy loads in perimeter zones by utilizing the combined design strategies of active systems and façade design variables. In addition, the effectiveness of design variables of diffusers in underfloor air distribution systems needs to be investigated.
- The input parameters used for sensitivity analysis are constrained to the envelope components, while other variables are assumed to be constant. Other relevant parameters such as building geometry, occupancy schedules, temperature setpoints, and air change rates should be considered in future studies.
- Because existing information about building factors and their bounds are still restricted, the number of input parameters and their ranges must be expanded, as with many other forms of SA research. Future studies might involve expanding the analysis to include those parameters or determining whether the same parameters for the same building would have a different degree of sensitivity if an energy modeling program other than IDA-ICE was used. As a future study recommendation, the same procedure might be applied for data from other regions to determine if the relevant input parameters change regionally.
- The sensitivity analysis exclusively addresses Budapest’s climate circumstances, using a single climate file, and cannot predict the impacts of climate change in the upcoming years. As a result, future studies should consider the consequences of climate change to provide more realistic results.

It is obvious that besides the advantages the geometrical simplifications might carry some limitations as well.

- Until now unreached quality level of design optimization evolves since testing of the significantly higher number of design cases in the same amount of available planning time is getting to be possible.
- The thermal zone geometry simplification's result inaccuracy level should be further reduced by compensation solutions for thermal mass and the central, deeper settled zone sections, which distort to a certain measure the simulation results.
- The described simplification methodology can be seen as the 1st step in a multi-level model simplification strategy, consisting of the next stages in simplifications techniques for fenestration, shading, thermal mass, HVAC systems, as well as controlling automation strategies.

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APPENDICES

Appendix A:

Table A1. Delivered energy for detailed and simplified models and their differences with respect to detailed model.

Delivered Energy	BS	S1	S2	S3	S4
Lighting, Facility (kWh)	9199	9209	9213	9205	9205
Difference %	0	0.1	0.1	0.1	0.1
Electric Cooling (kWh)	111501	122223	128313	123326	125104
Difference %	0	9.6	15.1	10.6	12.2
Electric Heating (kWh)	29755	28824	28716	29653	22723
Difference %	0	-3.1	-3.5	-0.3	-23.6
DHW (kWh)	4246	4246	4246	4246	4246
Difference %	0.0	0.0	0.0	0.0	0.0
Equipment, Tenant (kWh)	11746	11764	11750	11753	11761
Difference %	0	0.2	0.0	0.1	0.1
Total (kWh)	166447	176166	182237	178182	173038
Difference %	0	5.8	9.5	7.1	4.0

Table A2. Average number of annual hours of PMV, Category B for whole and some parts of the building in the detailed and simplified models and differences of simplified models with respect to detailed model.

	BS	S1	S2	S3	S4
	Average Annual Hours of PMV Category B				

Whole Building (hours)	7781	6642	7787	6906	7717
Difference %	0.0	-14.6	0.1	-11.3	-0.8
Second Floor (hours)	8026	6176	-	7646	-
Difference %	0.0	-23.1	-	-4.7	-
Third Floor (hours)	8063	8128	-	7928	-
Difference %	0.0	0.8	-	-1.7	-
South Side for 1,2,3 Floors (hours)	7900	-	8153	-	-
Difference %	0.0	-	3.2	-	-
North Side for 1,2,3 Floors (hours)	7921	-	5585	-	-
Difference %	0.0	-	-29.3	-	-

- = Zero (no value), as there was no simulation in this zone for the given scenario

Table A3. Average number of annual hours with CO_2 concentration > 1000 ppm for whole and some parts of the building in the detailed and simplified models and differences of simplified models with respect to detailed model.

	BS	**S1**	**S2**	**S3**	**S4**
	Average annual hours of CO_2 concentration > 1000 ppm				
Whole Building (hours)	2248	2130	2086	2058	2116
Difference %	0.0	-5.3	-7.2	-8.4	-5.9
econd Floor (hours)	2476	2473	-	1940	-
Difference %	0.0	-0.1	-	-21.7	-
Third Floor (hours)	2445	1249	-	2232	-
Difference %	0.0	-48.9	-	-8.7	-

South Side for 1,2,3 Floors (hours)	2249	-	2248	-	-
Difference %	0.0	-	0.0	-	-
North Side for 1,2,3 Floors (hours)	**2248**	**-**	**1858**	**-**	**-**
Difference %	**0.0**	**-**	**-17.4**	**-**	**-**

- Zero (no value), as there was no simulation in this zone for the given scenario

- **Table A4.** Thermal Zones properties in the investigated Building.

Thermal Zone	**Area (m^2)**	**Volume (m^3)**	**Glazing Area (m^2)**	**Glazing to Floor Area Ratio**	**Thermal Bridges (W/K)**
Zone 1	36.8	105.8	3.4	0.1	13.5
Zone 2	2.8	8.2	1.1	0.4	1.5
Zone 3	1.8	5.1	0.0	0.0	0.0
Zone 4	4.9	14.2	1.1	0.2	1.5
Zone 5	3.1	9.0	0.5	0.2	1.0
Zone 6	8.6	24.8	7.0	0.8	3.1
Zone 7	8.6	24.8	1.1	0.1	2.2
Zone 8	4.9	14.2	1.1	0.2	1.5
Zone 9	14.1	40.6	1.8	0.1	4.6
Zone 10	58.0	167.1	33.4	0.6	15.3
Zone 11	7.1	20.4	0.0	0.0	0.1
Zone 12	10.4	30.1	3.6	0.3	3.1
Zone 13	12.7	36.5	3.6	0.3	3.3

Zone 14	14.1	40.7	5.4	0.4	5.9
Zone 15	14.1	36.7	0.0	0.0	0.1
Zone 16	8.6	22.4	0.0	0.0	0.2
Zone 17	58.0	150.8	19.0	0.3	3.5
Zone 18	102.4	266.2	0.0	0.0	8.2