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Ph.D. Thesis Booklet

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

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1. INTRODUCTION

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. 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 and productivity. 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 concerns 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. Several design techniques, such as passive and active design solutions, could be regarded among building energy efficiency approaches. The passive design adapts to local climate and site circumstances to maximize building occupants' comfort and health while minimizing energy usage. 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 critical 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 advancements 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.

2. Problem Statement

In the context of global warming and decreasing natural energy resources, it is critical 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 CO2 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.

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. 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.

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 to 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 identifies 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 can proper 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.

4. New scientific results

The main results of my work are summarized in the following thesis

4.1. 1 st Thesis:

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, glazing pane are simulated by computational IDA ICE 4.7.

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, pane glazing, 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 pane glazing. On the other hand, infiltration represents the least effective passive strategy, thus, it is not recommended for building a hot and arid climate. 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. 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 requirements required some management of these passive techniques

4.2. 2 nd Thesis:

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 led to reduce the energy consumption of the dwelling. Also, study the impact of building location on energy consumption, especially when the latitude and weather are different through (Cairo, Aswan, and Alexandria).

The orientation of the structure is one of the most significant components in passive design since good orientation combines 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 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. The location has even more significant effect on energy consumption up to 67% in the investigated cases.

4.3. 3 rd Thesis:

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. 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. 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.

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 simplification approach is well applicable in further early-stage design and development tasks, specifically in large-scale projects. 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

4.4. 4 th Thesis:

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 results showed that the Materials 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, 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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