DETERMINATION OF BUILDING SHAPE FOR ENERGY EFFICIENCY USING SIMULATION AND PARTICLE SWARM OPTIMIZATION

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ABSTRACT

The building envelope shape is the most salient design characteristic and has a significant influence on energy consumption during the post-occupancy service life. However, during the conceptual design phase, envelope shape-finding is defined without considering post-occupancy service life energy performance. This warranted absence of a priori knowledge on shape-based convective heat transfer affects indoor environment quality and impedes the ability to meet post-occupancy energy performance efficiency requirements. In addition, there is no suitable method for designers by which to make such calculations. In an attempt to optimize energy consumption and reduce the post-occupancy service life in efficiency, this research aims to determine building shape energy efficiency using a simulation and optimization process that can facilitate the designer's task during the conceptual design phase. For this purpose, a case study research method and simulation-based particle swarm optimization process was conducted. Foremost, it is pertinent to understand building shape behavior in order to improve energy efficiency. For this, a longitudinal case study set out to collect real time energy data and historical building data by a selected unit of analysis Block C 02, Faculty of Geoinformation and Real Estate, Universiti Teknologi Malaysia. The building shapes were simulated using thermal transient simulation for heat transfer analysis. However, results indicated that a proportionate increase in building shape compactness, aspect ratio or coefficient can adversely affect building shape thermal performance, affirming the proposition that convective heat transfer and solar radiation have a considerable influence on energy consumption based on shape geometrical characteristics. Following this, a varied combination of shapes, wall window ratio and glazing energy performance was then analyzed using particle swarm optimization to determine the optimal envelope shape combination. The results confirmed that, as the shape achieves its geometric efficiency, it appropriates the wall window ratio and glazing proportions that reduce convective heat transfer. A design approach that can determine shape energy efficiency based on simulation and particle swarm optimization was then developed. Further, sensitivity of this design approach was calibrated using comparative testing and empirical validation. The findings provide a benchmark of energy consumption based on a combination of envelope shape characteristics, wall window ratio and glazing. In conclusion, this research has succeeded in transforming the conventional shape-finding process into an integrated simulation-based shape optimization for energy efficiency. The major contribution of this research study was that it developed a design approach for building shape energy efficiency and optimization. It can facilitate the task of designers during the conceptual design phase by disposing of their one-off design solutions and making it feasible to conceptualize varied building shapes for energy efficient design solutions.

ABSTRAK

Reka bentuk luaran bangunan ialah ciri reka bentuk paling penting dan mempunyai pengaruh yang ketara ke atas penggunaan tenaga semasa hayat perkhidmatan pasca penghunian. Walau bagaimanapun, semasa fasa reka bentuk konseptual, pencarianreka bentuk luaran ditentukan tanpa mengambil kira prestasi tenaga hayat perkhidmatan pasca penghunian. Ketiadaan pengetahuan mengenai pemindahan haba perolakan berasaskan bentuk mempengaruhi kualiti persekitaran dalaman dan menyekat keupayaan untuk memenuhi syarat-syarat kecekapan prestasi tenaga pasca penghunian. Sebagai tambahan, tiada kaedah yang sesuai untuk pereka membuat pengiraan sedemikian. Dalam usaha untuk mengoptimumkan penggunaan tenaga dan kecekapan hayat perkhidmatan pasca penghunian, kajian ini bermatlamat untuk menentukan kecekapan tenaga reka bentuk bangunan menggunakan proses simulasi dan pengoptimuman yang boleh memudahkan tugas pereka sewaktu fasa reka bentuk konseptual. Bagi tujuan ini, kaedah kajian kes dan simulasi berdasarkan proses pengoptimuman kerumunan zarah telah dijalankan. Antara yang paling utama adalah untuk memahami perlakuan reka bentuk bangunan supaya dapat meningkatkan kecekapan tenaga. Oleh itu, satu kajian kes longitudinal dijalankan untuk mengumpul data tenaga masa nyata dan data bangunan bersejarah dengan memilih unit analisis Blok C 02, Fakulti Geoinformasi dan Harta Tanah, Universiti Teknologi Malaysia. Reka bentuk bangunan telah disimulasi menggunakan simulasi sementara terma untuk analisis pemindahan haba. Namun begitu, hasil menunjukkan bahawa peningkatan berkadar dalam kepadatan reka bentuk bangunan, nisbah aspek atau pekali boleh memberi kesan buruk kepada prestasi terma reka bentuk bangunan, mengesahkan usul bahawa pemindahan haba perolakan dan radiasi suria mempunyai pengaruh yang banyak ke atas penggunaan tenaga berdasarkan ciri-ciri geometri reka bentuk. Susulan itu, kombinasi reka bentuk, nisbah tingkap dinding dan prestasi tenaga pelicauan yang berbeza kemudiannya telah dianalisa menggunakan pengoptimuman kerumunan zarah bagi menentukan kombinasi reka bentuk luaran yang optimum. Keputusan kajian mengesahkan bahawa, apabila reka bentuk mencapai kecekapan geometrinya, ia menyesuaikan nisbah tingkap dinding dan perkadaran pelicauan yang mengurangkan pemindahan haba perolakan. Pendekatan reka bentuk yang boleh menentukan kecekapan tenaga reka bentuk berdasarkan simulasi dan pengoptimuman kerumunan zarah telah dibangunkan. Selanjutnya, sensitiviti pendekatan ini telah disahkan menggunakan kedua-dua ujian empirikal dan perbandingan. Dapatan tersebut menyediakan tanda aras penggunaan tenaga berdasarkan kombinasi ciri-ciri reka bentuk luaran, nisbah tingkap dinding dan pelicauan. Kesimpulannya, kajian ini telah berjaya dalam mengubah proses dapatan reka bentuk lama kepada pengoptimuman reka bentuk berasaskan simulasi bersepadu untuk kecekapan tenaga. Sumbangan utama bagi kajian penyelidikan ini adalah ia membangunkan pendekatan reka bentuk untuk kecekapan dan pengoptimuman tenaga reka bentuk luaran bangunan.Ia boleh memudahkan tugas pereka sewaktu fasa reka bentuk konseptual dengan mengatur penyelesaian reka bentuk sekali mereka dan boleh dilaksanakan untuk mengkonsepsikan pelbagai reka bentuk luaran bangunan untuk penyelesaian reka bentuk cekap tenaga.

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LIST OF ABBRIVIATIONS

ASHRAE	-	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BREEM	-	Building Research Establishment Environmental Assessment Method
CAD	-	Computer Aided Drafting
CEN	-	European Committee for Standardization
CFD	-	Computational Fluid Dynamics
GBI	-	Green Building Index, Malaysia
HVAC	-	Heat, Ventilation and Air conditioning
IAQ	-	Indoor Air Quality
IESNA	-	Illuminating Engineering Society of North America
IEQ	-	Indoor Environment Quality
LEED	-	Leadership in Energy and Environmental Design
PSO	-	Particle Swarm Optimization
SBS	-	Sick Building Syndrome
SHGC	-	Solar Heat Gain Coefficient
Tvis	-	Glass visible transmittance
UNDP	-	United Nation Development Programme
WBDG	-	National Institute of Building Sciences,
WWR	-	Wall Window Ratio

LIST OF SYMBOLS

C_f	-	Shape coefficient
Q_{wc}	-	Heat conduction through opaque walls
Q_{gc}	-	Heat conduction through window glass
Q_{sol}	-	Solar radiation through window glass
r_c	-	Relative compactness
S_e	-	Envelope surface area
S_c	-	Compactness
SF	-	Solar factor of fenestration
T	-	Temperature
TV	-	Thermal transfer
U_f	-	U value of fenestration
d	-	Dimension
ν	-	Velocity
v	-	Inner volume of the building
w	-	Inertia
ω	-	Magnitude

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CHAPTER 1

INTRODUCTION

1.1 Research background

In Malaysia, buildings account for 40% of total energy use and 36% of total CO_2 emissions (Ahamed *et al.*, 2011). According to Adalberth (1997), 65% of the total energy use was consumed during the operation phase, which is post-occupancy, rather than the construction and demolition phases. For instance, in the building life cycle energy phase of a building (i.e. pre-use, use-phase, maintenance and demolition phase), in particular the building use-phase (operation phase) energy utilization is much higher than other phases due to failures. This increasing energy demand is foreseen as a Facilities Management (FM) maintenance threat that gradually affects resultant performances and increases the life cycle cost by 15% (Da Silva *et. al.*, 2012). This is an indication of the importance of reducing post-occupancy phase energy consumption. For instance, FM comprises and integrates multiple disciplines (i.e. people, place, technology and process). These partly render their services for the up-keep of the implicit building performance maintenance aspects such as indoor thermal comfort, IAQ, IEQ, energy maintenance as well as occupant health and hygiene that predominantly contribute to the success of the core competency of business productivity (Al Horr *et al*., 2001). In a trending business requirements environment, if productivity is to be achieved it is pertinent to provide high performance solution space that meets optimal indoor environment quality and thermal comfort conditions. This requires a better air exchange rate that can be achieved only by heavy utilization HVAC that prevents heat gain. Consequently, this increases post-occupancy service life energy consumption in terms of energy use in buildings (Asif, Muneer and Kelley, 2007). According to Gupta and Chandiwala (2010), issues of thermal comfort, IAQ, IEQ and lighting control are regulated only by building envelope attributes in order to prevent thermal transfer. For instance, building envelope performance is one of the intervening causes for heat gain, as well as a poor air exchange rate which can influence thermal comfort and humidity (Bell *et al*., 2010). This contributes to a negative effect that causes deterioration of indoor environmental quality, sensorial disturbances and psycho-social illnesses (i.e. stress, sick building syndrome) thereby depriving occupants of productivity (Gou and Lau, 2012; Aguilera, *et al*., 2013). However, energy consumption and energy use varied by occupant archy-type and behavior might also contribute to performance failure (Roetzel and Tsangrassoulis, 2012). However, it was largely affected by not considering pre-requisites of facility management's energy maintenance in order to achieve energy efficiency during the conceptual design phase (Eberhard, 2003; Hossein *et al*., 2013). This further resulted in 11% of performance failures, namely: 40% energy loss annually attributed to the design of that account for 50% and failure to respond to abrupt climate changes (Rivar *et al*.,1995). This led to a deviation in actual energy performance as predicted in design (Roetzel and Tsangrassoulis, 2012). The deeper underlying factors for this energy performance failure and gap, namely, the implementation of sustainable passive design standards, policies and framework are believed to contribute towards optimistic design predictions that achieve energy efficiency (Hernandez and Kenny, 2010; Tofield, 2012; Attia *et al*., 2013). In addition, envelope designs that need to be tested quantitatively are often overlooked by designers (Gucyeter and Gunaydin, 2012). This comes about because designers focus on solving spatial design issues that do not proceed by form following function nor do they bother to adhere to energy efficiency issues during the conceptual design phase (Torres and Sakamoto, 2007; Cetiner and Edis, 2013). This has warranted flexibility for changing needs as part of building shape requirements for diminished performance optimization (Catalina and Iordache, 2012). On the other hand, a one-off design solution drastically reduces the possibility of shape behavior being examined to achieve reliable energy efficiency (Coelho and de Brito, 2013). In such a complex iterative design process, a designer may not be able to fully realize and predict energy performance, since energy systems in buildings are relatively complex and there exists a high probability for over-specifying HVAC (Maile, Fischer and Bazjanac, 2007; Yassin, 2011). This has resulted in an inadvertent increase in post-occupancy energy consumption. Hence, this proves there is a dearth of knowledge in envelope shape design, size, window and glazing that could support

HVAC efficiency. On the other hand, there is currently no approach that establishes envelope combinatorial performance quantitatively for better design decision-making. Therefore, the prevailing methods for predicting the energy of buildings during the design stage are rudimentary for design application. This vindicates the theory that envelope shape design attributes reduce energy consumption and act as a system/sub-system to provide climate response, (Sozer, 2010; Stavrakakis *et al*., 2012c; Favoino *et al*., 2014). Therefore, it is pertinent to augment envelope shape design using simulation and optimization methods that can reduce the energy performance gap.

1.1.1 Building envelope energy performances

Building envelope design has become an integral part of a sustainable building design approach that regulates total building performance attributes including: energy performance; indoor environmental quality; provision of protection from extreme outdoor heat; humidity control; thermal affects and prevention of noise (Jin, Overend and Thompson, 2012). Su and Zhang (2010) argued that envelope design has the greatest influence on life cycle building energy and accounts for more than 50% of the energy performance gap and post-occupancy performance failure. For instance, excessive window glazing in envelope design accounts for more than 30% of the heat gain and thermal radiation into indoor space (Department Energy Studies, USA, 2012) (Gucyeter and Gunaydin, 2012; Cetiner and Edis, 2013). According to Gustavsen *et al*. (2010) large panes of glazing may contribute to high thermal convection and radiation that can lead to excess heat flux that increases indoor envelope surface temperature. Kim (2011) argued that an undesired solar load causes penetration of not only light, but radiation of 87% to 95%. Consequently, this results in either a heat loss or heat gain effect on post-occupancy energy consumption. Similarly, state-of-the-art window technologies, calculation of ratio between wall and window (Wall Window Ratio (WWR)) and glazing distribution by solar heat gain co-efficient (SHGC) and corresponding lower U value might not adequately represent building energy consumption (Goia, Perino, and Serra, 2013). This can result in the design of a wall window ratio that adversely affects indoor thermal comfort and causes sick building syndrome (SBS) (Jones, Lannon, and Williams, 2001; Cetiner and Edis, 2013). It is further justified by Bhola *et al.* (2000) who stated that even 20% thermal mass discrepancy in an envelope may affect occupant thermal comfort in a mechanically-ventilated building (i.e. air-conditioned building). Considering the issues pertaining to energy consumption, Konis (2013), confirmed that lack of focus on envelope shape during the conceptual design phase posed a challenge that could impact on energy performance failure. In addition, the arguments of Goia *et al*. (2013) proved that without an appropriate geometrical profile, designers fail to gauge the accuracy of energy performance only by envelope materials. This proves that building shape characteristics such as compactness, coefficient and aspect ratio influences heat transfer, in addition to window and glazing combination. Therefore, it is pertinent to have appropriate shape characteristics during the conceptual design stage.

Envelope shape is usually defined in the early design stages and is most likely to suffer little change until the end of the design process. The energy consumption values are never calculated during the conceptual design phase, due to a lack of design information and extensive modelling requirements for energy simulation. These are considerably time-consuming, as the design of the shape is mostly performed by "rule of thumb" (Goia *et al*., 2013). Although the guideline facilitates the role of the designer, it is often not sufficient for more complex design projects. Therefore, in a long building lifecycle the issue of building shape plays a pivotal role in improving the resultant performance of the buildings (Huang *et al*., 2007). Therefore, choice of building shape is significant in the case of achieving energy efficiency (Wang *et al*., 2006). Enforcing regulation through envelope shape efficiency can assess the shape behavior against heart transfer variables such as radiation and thermal infliction which could prevent energy performance failure. To achieve shape-based energy optimization, there is a need for a divisive design approach that can aid a designer during the conceptual design phase.

1.1.2 Building envelope methods, approaches and simulation in design process

In design, applications of simulation and optimization are in the frontline to address building energy performances issues. They are mostly concerned with addressing discrete variables such as building materials, insulation, glazing type and shading devices respectively. For example, Kim (2011) describes a design of carbon reduction method which used low-E-coated glass. This is a transparent composite façade system which failed to reflect heat and counter heat gain or heat loss. Similarly, Gou and Lau (2012), and Tzempelikos, Athienitis, and Karava (2007), developed an alternate method that uses operable window and shading devices to curb heat gain. Susorova *et al*. (2013), found that an embedded vegetative technique might improve thermal behavior by preventing evapo-transpiration and convective heat exchange between vegetation and an envelope layer. Cetiner and Edis (2013), studied various proportions of WWR for building an envelope that considered orientations, dimensions and thermal insulations. Su and Zhang (2010) suggested a life cycle assessment approach that analyzed the environmental impact of envelope heterogeneous variables such as window types and WWR. Although Goia *et al*. (2013) proved how robust window design could reduce heat gain and heat loss from 9% to 15%, this still depends largely on window type (i.e. super window). However, the life cycle assessment that is made for windows does not seem to contain viable decision methods during the conceptual design phase. Further, it is less predictable without adequate design information. Therefore, Choi, Loftness and Aziz (2012), ascertained that a less-informative design phase (i.e. conceptual design) is advisable by which to use widely-accepted design-based IEQ guidelines (i.e. Building Research Establishment Environmental Assessment Method; LEED- The Leadership in Energy and Environmental Design; HK-BEAM – Hong Kong Building Environmental Assessment Method; and BEES-Building for Environmental and Economic Sustainability) so as to help a designer. However, Catalina *et al*. (2013), argued that most performance failures occurred due to the lack of a reliable expert system that could integrate design data such as shape, WWR, climate data, orientation, envelope material properties, and window properties respectively.

The research noticed an increasing tendency to use more simulation and optimization during the detailed design phase. For instance, Bouchlaghem (2000) proposed a graphical model that can simulate thermal performances; this could be applicable during the detailed design phase. The graphical model requires detailed information such as envelope material characteristics that were not available during the conceptual design phase. Sozer's (2010) multi-criteria decision-making approach tested the thermal performance of single glass with insulated window, double glazed window and Low-E glass components respectively. According to Rapone and Saro (2012), thermal comfort index is not achievable without 'U' value. Findings from these studies indicated that there is a possibility to curb latent radiation but composition of glazing, shading devices alone is not an efficient mechanism by which to obtain optimum facade performance. Therefore, Zemella *et al*. (2011) proved that single objective and multi-objective optimization can enable designers to select envelope options based on energy consumption range but not cause an inflictive relation between the variables. Therefore, Han *et al*. (2007), proposed a regression model that could evaluate heterogeneous variables (i.e. U values, orientation, shading devices, length). Similarly, according to Leskovar and Premrov, (2011), mathematical interpolation considers a number of variables such as material properties, plan aspect ratio, ceiling heights, orientations, ventilation rate, glazing and shading. However, through the use of multi-criteria optimization, it is possible to achieve total performance, but inflictive variance for WWR is not achievable and was not applicable during the conceptual design phase (Jin, Overend and Thompson, 2012).

The challenge for the above-discussed studies is to design and identify the optimal solution for facade based on solar radiation, IEQ performance, window performances and glazing respectively. Considering an exclusive set of conditions might not be feasible to make an appropriate design decision during the conceptual design phase. This proves that facade performance is not defined solely by homogenous variables that set energy inertia for optimization. Very few studies have addressed in combination the elements of façade, using two and not more than four variables. The empirical evidence of post-occupancy data proves that envelope variables are inter-related, which inflict upon one another for heat transfer. Encouraging the application of these methods during the conceptual design stage has failed to facilitate the task of a designer and is possible only with larger design data that could be obtainable during a detailed design phase. This research emphasizes that the resultant performance failure in building is influenced by combinatorial envelope variables that were not researched to a large extent. In addition, none of the above studies considered the use of the shape variable to find their relative effect on WWR and glazing proportion. Therefore, this research posits that there is a lack of a holistic approach that could identify appropriate shape, WWR and glazing for energy efficiency during the conceptual design phase.

1.2 Problem statement

The envelope shape of a building is the most salient design characteristic and has a significant influence on energy consumption during the post-occupancy service life of the structure. However, during the conceptual design phase, envelope shape-finding is defined without considering the energy performance required during post-occupancy service life. This warranted absence of a priori knowledge on shape-based convective heat transfer affects indoor environment quality and can impede post-occupancy energy performance efficiency. For instance, poor building shapes and inadequate proportions of WWR and glazing are recognized as significant causes for undesired heat gain and thermal convection (Konis, 2013). This influence of thermal discomfort and poor indoor environmental quality has become a prime cause for occupant sensorial unpleasant symptoms and psycho-social illness (sick building syndrome). Furthermore, the larger deviation between the designed building and the actual built energy performance, proves that a designer could not efficiently gauge the accuracy of energy assumptions during the conceptual design phase (Stiny, 2006; Fernandes *et al*., 2014). The approaches and methods that were discussed in Section 1.1.2 addressed only homogenous envelope variables and not a combination of factors (i.e. WWR and glazing; glazing kind and shading devices; window types and shape). These sought to improve indoor environmental quality and energy performance efficiency. Therefore, not enough investigation has been conducted into the pursuit of validating the building envelope shape variables in combination such as shape compactness, coefficient, aspect ratio, WWR and glazing against heat transfer variables. This proved that the research gap is significant in order to reduce design-influenced energy performance failure and variance in post-occupancy energy consumption. Therefore, it can be seen as a phenomenon that needs further investigation so as to develop a simulation-based optimization approach that facilitates the task of the designer during the conceptual design phase. To address the research problem, this study developed two main research questions (RQ). RQ 1 seeks to investigate the landscape of post-occupancy energy performance issues, failures pertaining to envelope design and formulation of combinatorial variables that influence post-occupancy energy performances. RQ 2 is further divided into three sub-RQs which aim to answer the following: shape influenced energy performance; identification of appropriate shape combinations; and developing a designer approach for energy efficiency. This approach enables a designer to quantify the impact of envelope shape and compare it with swarm of various design alternatives for ‘n’ best design solutions. Answering these research questions develops a benchmark for various shape compactness in order to achieve optimal thermal and energy performances.

RQ 1: What are the combinatorial design-based envelope variables that affect the energy performance?

RQ 2: How can appropriate building shape for energy optimization be identified?

Sub RQ 2a: How does building shape influence post-occupancy energy performance?

Sub RQ 2b: What is the appropriate envelope combination (building shape, WWR and glazing) needed to improve energy optimization?

Sub RQ 2c: How can a design approach that will enable designers to predict building shape behavior against energy performance be developed?

1.3 Proposition

Based on the extensive review of envelope energy performance issues and identified research problems, this research theorized two propositions that needed to be tested by simulation. Through the formulation of Proposition 1 and Proposition 2, this study answers the research questions. Proposition 1 examines the various primitive and non-primitive building shape energy performance behavior and identifies their relationship with heat transfer variables. Proposition 2 theorized based on WWR and glazing proportions a combinatorial relationship with shape that inflicts a heat transfer variable. Both these propositions set the way forward to developing an approach that could determine building shape efficiency during the conceptual design phase.

Proposition 1: For a building shape that influences energy performance

"Proportionate increase in either building shape compactness, aspect ratio or coefficient adversely affects the building shape thermal performance such as heat transfer. Similarly, solar radiation has a high influence on energy consumption based on shape geometrical characteristics"

Proposition 2: For appropriate shape, WWR and glazing combination

"As the shape compactness, shape coefficient and aspect ratio achieves its geometric efficiency, appropriate WWR and glazing proportions that optimize energy performance are developed".

1.4 Aims and objectives

The aim of this research is to determine building shape energy efficiency using simulation and optimization. This is expected to enhance the building shape-finding process during the conceptual design stage in order to obtain an effective building shape that could achieve energy efficiency. However, there is a distinctive difference in conceptualizing a building shape that considers various design constraints in an iterative design process (Jaganathan *et al.*, 2013). Nevertheless, if the shape-finding process integrates simulation and optimization during the conceptual design stage, it is possible to predict accruable energy performance and curb design-influenced energy performance failure. This approach examines the shape energy performance behavior during the conceptual design phase and enables a designer to find the best fit shape-based design solution and reduce post-occupancy performance failures.

The aim of this research is to achieve a break-down of the following objectives. In pursuit of addressing the issue of shape-based energy optimization, the first objective investigates energy performance issues and design failures. Thus, there is a requirement to formulate variables that need to be considered during the conceptual design phase. These justified, shape-based variables need to be incorporated into the thermal transient simulation process. The second objective is to simulate the various primitive and non-primitive building shapes so as to understand the energy performance behavior pertaining to the heat transfer variable and identify their relationship. Thus, we proceed to the third objective which is to develop a design approach for energy efficiency that can facilitate the task of the designer during the conceptual design phase.

Objective 1: To formulate envelope shape variables that influence post-occupancy energy performance.

Objective 2: To investigate various building shape influences on energy performances by simulation.

Objective 3: To develop a design approach for building shape energy optimization

1.5 Research methodology

Many design researchers conducted a simulation to evaluate building performance considering homogenous and heterogeneous variables (Mc Keen and Fung, 2014; Mangkuto, Rohmah and Asri, 2016). In particular, the meta-heuristic evolutionary multi-objective optimization algorithm (i.e. genetic algorithm, artificial neural network and particle swarm optimization) was the applied method by which to estimate, evaluate and predict energy performance, IAQ, and IEQ. For instance, Holst (2003) used a genetic optimization approach and energy in their case study in order to minimize energy use and developed a comfort metric for indoor environmental comfort. Similar approaches were carried out by Torres and Sakamoto (2007) and Gagne and Anderson (2010); both used a genetic algorithm to achieve optimized daylight availability. To determine a link between design and post-occupancy energy performance, Bambrook *et al*. (2011) and Schnier and Gero, (1998) used a "brute-force" method and e-quest to minimize energy use and reduce carbon emissions. This was achieved by varying building fabric properties such as glazing and mechanical ventilation of a building. Most of the said meta-heuristic approaches evaluated heterogeneous envelope variables such as: windows; type of glazing; glazing proportions; and shading devices for energy optimization (Al-Homoud, 1997a, 2005b; Caldas and Norford, 2003; Torres and Sakamoto, 2007; Znouda *et al*., 2007; Wright and Mourshed, 2009; Manzan and Pinto, 2009). These studies justify the use of a coupled approach for simulation energy performance optimization. On this basis, the current study investigates shape energy performance behavior as against heat transfer variables by using CFD simulation and particle swarm optimization. Further, Coley and Schukat (2002) affirm that, in order to collect multiplicity of empirical data, the case study is an appropriate approach through which simulation and Particle Swarm Optimization (PSO) could be explored. This case study approach enables the simulation of the effect of thermal flow impact on primitive and non-primitive shape cooling load.

The case study approach was employed to collect real time data by way of interviews, direct observations, and archival data (i.e. building information) which enabled a base line model to be developed. With the help of a baseline model, transient simulations were conducted for primitive and non-primitive building shapes as against heat transfer and radiation. Varied combinations of shape energy performances were optimized by using particle swarm optimization to find 'n' best envelope shape combination. The outcome of this approach was further validated by using sensitivity analysis for calibration. The case study research and their components are briefly discussed and shown in Figure 3.1 in Chapter 3.

1.6 Significance of research

This study supports the integration of a shape-based energy efficiency design solution during the conceptual design phase that uses simulation and optimization respectively. Moreover, the study supports the possibility to predict accruable post-occupancy service life energy performances. It can also help a designer to select energy efficiency based design solutions in several design alternatives and discard one-off design solutions. It has the potential to close the gap between the accruable energy performance during the conceptual design phase and actual energy performance during post-occupancy service life. Furthermore, extensive investigations of the past thirty years of research works and empirical data clearly proves that considering energy optimization is most important during the conceptual design phase to reduce post-occupancy performance failures. A thorough literature review has indicated the knowledge gap; that is, there is a need for an approach that should be developed based on building shape energy efficiency. For instance, it was determined that the lack of a holistic design approach, studies relating to building energy performance and their findings were conceptual and could be attributed to post-occupancy performance failures. Secondly, existing optimization models, recommendations and guidelines (i.e. BREEAM, LEED, HK-BEAM, BEES, GBI-Malaysia) that fail to consider design variables such as shape, besides material input in a detailed iterative simulation were considered. Moreover, most of the approaches that were complex and time-consuming could be used only in the detailed design stage. Lastly, literature reiterates that post-occupancy energy performance failures in buildings adversely affect total building performances such as IEQ, thermal performance, health and hygiene, and occupant productivity. To overcome all these energy performance failures, it is necessary to develop a design approach that can incorporate shape-based energy optimization during the conceptual design phase. Therefore, the study sets the investigation strategically in two major phenomena that are lacking in the contemporary design approach:

I. Envelope shape design should respond to post-occupancy energy performances.
II. It is necessary to develop an integrated optimization approach during the conceptual design phase with reference to case-based building energy performance for reducing design failures.

1.7 Organization of the thesis

This thesis is organized into six chapters as follows.

Chapter 1 presents the research background, problem statement, research question, aims and objective of this research, summary of research methodology and significance of research study.

Chapter 2 presents a thorough literature review related to this research work. In this chapter, the discussion sets its focus on post-occupancy energy performance failure, design led flaws in performance gap, governing performance envelope attributes in addition to energy performances methods, measures, and models. The knowledge gap is outlined and discussed with the need for methods that identify the envelope shape and optimization models during the design phase.

Chapter 3 presents a review of research approaches relevant to this study and makes comparisons for identifying suitable research methods. The research framework explains components of case study, baseline model for transient simulation of various shape cluster energy consumption and optimization methods to identify appropriate envelope shape. Lastly, the approach is validated using sensitivity analysis for calibration.

Chapter 4 presents the results and analysis of data collected during the case study as explained in Chapter 3. Reporting the findings relies on simulation of various shape cluster results. Results of shape cluster are interrelated with shape and heat transfer variables.

Chapter 5 presents the discussion of major findings of simulations and validation of the design approach that has been developed. The first part of this chapter is dedicated to discussion of various shapes' energy consumption while the second part elaborates upon the evolutionary design approach. The last section describes the two step validation process for the evolutionary optimization approach for envelope shape design.

Chapter 6 summarizes the whole thesis and its findings. It discusses the usefulness of the simulation and optimization approach during the conceptual design phase. The optimization approach is described and recommendations for further research when applying integrated simulation and optimization are also provided. Finally, the chapter concludes by highlighting the knowledge contribution of the thesis as well as its impact on professional practice.

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