DEVELOPMENT OF ENERGY-EFFICIENT BUILDING ENVIRONMENTAL QUALITY EVALUATION FRAMEWORK

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Dedicated to my beloved parents, sister, brother and all my friends

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ABSTRACT

This research is about the development of an energy-efficient building environmental quality evaluation framework for office building in hot and humid climatic regions. The aim of this research is to develop an evaluation framework for the identification of problems with respect to energy-efficient design affecting occupants' comfort. This research focuses on the application of energy-efficient design in office building; secondly, identifies the effects of energy-efficient design problems towards occupants' comfort; and finally proposes an evaluation framework for the rating of energy-efficient design problems which affect the occupants' comfort. This research was conducted at three energy-efficient buildings in Malaysia. A new building performance evaluation framework Energy-efficient Building Environmental Quality Evaluation Framework has been constructed and tested at the selected energy-efficient buildings. The tested results were then analyzed using Statistical Package for Social Science (SPSS) in order to determine its reliability and validity. The research outcomes have shown high reliability and validity of the validated newly designed evaluation framework. In conclusion, this research has shown that the newly designed Energy-efficient Building Environmental Quality Evaluation Framework is able to identify the occupants' comfort level in energy-efficient building and the causes of the problems which is mainly due to the building envelop such as shading and window features of the energy-efficient building.

ABSTRAK

Kajian ini adalah mengenai pembangunan rangka kerja penilaian kualiti persekitaran bangunan bagi bangunan pejabat yang terletak di kawasan beriklim khatulistiwa, kajian ini bertujuan untuk membangunkan satu rangka kerja penilaian bagi mengenal pasti masalah-masalah reka bentuk cekap tenaga yang mempengaruhi keselesaan penghuni. Kajian ini bertumpu pada aplikasi reka bentuk cekap tenaga dalam bangunan pejabat, kedua, mengenal pasti kesan daripada masalah-masalah reka bentuk cekap tenaga yang mempengaruhi keselesaan penghuni dan akhir sekali, mencadangkan rangka kerja penilaian bagi mengenal pasti masalah reka bentuk cekap tenaga yang mempengaruhi keselesaan penghuni. Kajian ini dijalankan di bangunan cekap tenaga yang terdapat di Malaysia. Satu rangka kerja penilaian prestasi bangunan yang baru, Rangka Kerja Penilaian Kualiti Persekitaran Bangunan telah dirangka dan diuji di bangunan-bangunan cekap tenaga yang terpilih. Keputusan pengujian dianalisis dengan menggunakan perisian pakej statistik untuk sains sosial atau *Statistical Package for Social Science* (SPSS) bagi menentukan kebolehpercayaan dan kesahannya. Hasil dapatan kajian menunjukkan Rangka Kerja Penilaian Kualiti Persekitaran Bangunan mempunyai kebolehpercayaan dan kesahan yang tinggi. Kesimpulannya, kajian ini telah menunjukkan Rangka Kerja Penilaian Kualiti Persekitaran Bangunan ini mampu mengenal pasti tahap keselesaan penghuni di bangunan cekap tenaga dan punca pada masalah keselesaan penghuni adalah disebabkan kedudukan tingkap and pengadang yang digunakan di bangunan cekap tenaga yang dikaji.

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LIST OF SYMBOLS AND ABBREVIATIONS

%	-	Percents
CO_2	-	Carbon Dioxide
CVR	-	Content Validity Ratio
hrs/wk	-	Hours per week
kW	-	Kilowatt
kWh	-	Kilowatt-hour
kWh/m^2	-	Kilowatt hours per meter square
$kWh/m^2/yr$	-	Kilowatt hours per square meter per year
kWh/year	-	Kilowatt hours per year
m	-	Meter
m^2	-	Square meter
MJ	-	Mega joule
mm	-	Millimeter
n/2	-	number of panelists divided by two
n_e	-	number of panelists indicating "essential"
r	-	rho
Tvis	-	*Visible Transmittance*
α	-	Alpha
AHU	-	Air Handling Unit
AIA	-	American Institute of Architects
APEC	-	Asia-Pacific Economic Cooperation
ASEAN	-	Association of Southeast Asian Nations
ASHRAE	-	American Society of Heating, Refrigerating and Air Conditioning Engineers
BASE	-	Building Assessment Survey and Evaluation
BEI	-	Building Energy Index

BIPV	-	Building Integrated Photovoltaic
BIU	-	Building-In-Use
BQA	-	Building Quality Assessment
BREEAM	-	BRE Environmental Assessment Method
BS5240	-	Industrial Safety Helmets - specification for construction and Performance
BUS	-	Building Use Studies
CBE	-	Center for the Built Environment
CDC	-	Centers for Disease Control and Prevention
CFL	-	Compact Fluorescent Lamp
CMC	-	Chilled Metal Ceiling
COPE	-	Cost effective Open Plan
CPEC	-	Car park Energy Consumption
CRT	-	Cathode Ray Tube
CVI	-	Content Validity Index
DCA	-	Data Centre Area
DCEC	-	Data Centre Energy Consumption
DDC	-	Direct Digital Control
DTU	-	Danmarks Tekniske Universitet
EEBEQ	-	Energy-efficient Building Environmental Evaluation Framework
EDPM	-	Electronic Data Processing Machine
EEMP	-	Energy Efficiency Master Plan, Malaysia
EMS	-	Energy Management System
ERV	-	Energy Recovery Ventilation
ETP	-	Engineering Thermoplastic
FVR	-	Weighted Floor Vacancy Rate
GBI	-	Green Building Index
GEF	-	Global Environment Facility
GEO	-	Green Energy Office
GFA	-	Gross Floor Area
GLA	-	Gross Lettable Area
HFSQ	-	Human Factors Satisfaction Questionnaire

HOPE	-	European Health Optimization Protocol for Energy-efficient buildings
HVAC	-	Heating, Ventilating, and Air Conditioning
IAQ	-	Indoor Air Quality
ICC	-	Intra-class Correlation Coefficient
ICIEE	-	International Center for Indoor Environment and Energy
IEQ	-	Indoor Environmental Quality
KeTTHA	-	Ministry of Energy, Green Technology and Water, Malaysia
KKR2	-	Kompleks Kerja Raya 2
KL	-	Kuala Lumpur
KLCC	-	Kuala Lumpur City Center
LCD	-	Liquid Crystal Display
LED	-	Light-Emitting Diode
LEED	-	Leadership in Energy and Environmental Design
LEO	-	Low Energy Building
MIEEIP	-	Malaysia Industrial Energy Efficiency Improvement Project
MIT	-	Massachusetts Institute of Technology
MPS	-	Mapping previous study
MS 1525:2001	-	Code of Practice on Energy Efficiency and use of Renewable Energy for Non-residential Buildings
PC	-	Personal Computer
PCM	-	Phase Change Material
PEX	-	Cross-linked polyethylene
POE	-	Post Occupancy Evaluation
PROBE	-	Post-occupancy Review of Buildings and their Engineering
PV	-	Photovoltaic
REF	-	Ratings of Environmental Features
RIBA	-	Royal Institute of British Architects
RSF	-	Research Support Facilities
SBS	-	Sick Building Syndrome

SC	-	Shading Coefficient
SCATS	-	Smart Controls and Thermal Comfort
SHGC	-	Solar Heat Gain Coefficient
SPSS	-	Statistical Package for the Social Sciences
SRI	-	Solar Reflectance Index
SSSH	-	Self-Sufficient Solar House
TBEC	-	Total Building Energy Consumption
TBP	-	Total Building Performance
UBBL	-	Uniform Building By-Laws, Malaysia
UCB	-	University of California, Berkeley
UK	-	United Kingdom
UNDP	-	United Nations Development Program
UNEP	-	United Nation Environment Program
USA	-	United States of America
VAV	-	Variable Air Volume
VFD	-	Variable-Frequency Drive
VOCs	-	Volatile Organic Compounds
VSD	-	Variable-Speed Drive
VT	-	Visible Transmittance
WHO	-	Weighted Weekly Operating Hours
ZEB	-	Zero Energy Building
ZEH	-	Zero Energy Home

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CHAPTER 1

INTRODUCTION

1.1 Background of research

This research is about the development of an energy-efficient building environmental quality evaluation framework for office building in hot and humid climatic regions. According to the National Institute of Building Sciences (2008), human comfort is one of the important aspects needed to be taken into account while developing an energy-efficient building. Therefore, the development of energy-efficient building environmental quality evaluation framework involves identifying the occupants' comfort level in energy-efficient building through its assessment criteria such as thermal comfort, lighting, acoustics and indoor air quality (IAQ). Such effort could help to prevent repeating past mistakes particularly from the aspect of occupant's comfort in the future development of energy-efficient building.

In this study, the term "energy-efficient building" is used as a collective term for different types of buildings made to reduce energy consumption; and the aim of these buildings is to cope with the problems derived from the over consumption of natural resources mostly coal, which is used by building during its operational process. At present, there are three office buildings specifically designed with energy-efficient features in Malaysia, (1) Ministry of Energy, Communications, and Multimedia office building or well known as Low Energy Office (LEO); (2), Green Energy Office (GEO) which housed the office building for Malaysia Green Technology Corporations; and (3), Energy Commission office building or known as ST Diamond.

These buildings are the initiatives demonstrated by the government to fully engage in the sustainable development (United Nations Environment Programme, 2011).

1.2 Problem statement

The development of a sustainable building rating system such as Leadership in Energy and Environmental Design (LEED), and Malaysian Green Building Index (GBI) reflected the current focus of the building performance objectives mostly on *optimizing energy and resource efficiently*. Although the current focus on building energy performance is high yet some of the buildings particularly energy-efficient buildings are still not able to achieve the low energy consumption in terms of the yearly energy use. Newsham *et al*. (2009) analyzed the data supplied by the New Buildings Institute and the US Green Buildings Council on measured energy use data from 100 LEED-certified commercial and institutional buildings and had found that 28–35% of LEED buildings use more energy than their conventional counterparts. A study by the New Building Institute (2008), also found about 30% of LEED rated buildings perform better than expected, 25% perform worse than expected and a handful of LEED buildings have serious energy consumption problems. These problems are due to repetition of past mistakes by creating unnecessary and wasteful complexity, which can undermine the green buildings' whole purpose (Leaman & Bordass, 2007).

The inefficiency of the current energy-efficient buildings' performance might be caused by the overlook of the importance of buildings' Indoor Environmental Quality (IEQ). According to Department of Energy (2001), in the development of energy efficiency program for building, it is important to appreciate that the fundamental purpose of the building is to serve occupants and their activities rather than to save nor use energy. The above statement was further supported by Heerwagen & Zagreus (2005). From the research they had conducted, they found out that sustainable building design strategies are able to create improved indoor environmental quality (IEQ) and should thus be associated with improved occupants' comfort, satisfaction, health, and work performance relative to buildings designed around standard practices. The improvement of work performance could also serve as a strong stimulus for energy conservation measures that simultaneously improve indoor environments (Fisk, 2000). The importance of building's IEQ especially in energy-efficient buildings has led to the development of Health Optimization Protocol for Energy-efficient Buildings (HOPE) project, a research funded by European Union countries that aims to create healthy and energy-efficient buildings in the region (Bluyssen & Loomans, 2003).

A research done by Baird *et al.* (2011) shows that the perception of the user towards "sustainable building are better than the "conventional building" in terms of IEQ aspects such as lighting, noise, temperature and air quality. In another study, users have high degree of satisfaction toward overall performance of energy-efficient building (Zainordin, Abdullah & Ahmad, 2012). A research carried out by Ismail & Sibley (2006) show that bioclimatic high rise office building creates a better working environment for the users and provides higher level of satisfaction than conventional ones. The passive design strategies that apply in energy-efficient building in Malaysia on the average, proven effective at improving indoor thermal comfort, which in turn lead to improving occupant satisfaction. Besides high level of users' satisfaction towards energy-efficient buildings, empirical result also show indoor thermal and ventilation condition in bioclimatic buildings are better than that of conventional ones (Ismail, Sibley & Wahab, 2011).

Evidence from recent post-occupancy evaluations done by Abbaszadeh *et al.*, (2006) also found potential for green building to enhance the IEQ. However, they often fall short. Their research found that although some of the best green buildings can rank higher than the best conventional buildings in terms of occupants experience towards comfort, health and productivity, a few of the lowest scoring buildings on user experience are also reported as green building or energy-efficient building. According to Wall (2006), many buildings, once in operation, are not as energy-efficient and thermally comfortable as expected. Research on comparing the comfort level of green buildings and conventional buildings conducted by Paul & Taylor, (2007) concluded that, there was insufficient evidence to support that green buildings are more comfortable than conventional buildings, particularly, with respect to aesthetics, serenity, lighting, ventilation, acoustics, and humidity. A similar outcome from the research carried out by Hinge *et al.* (2008) also shows that some of the energy-efficient buildings actual performance is quite different from their predicted performance, especially for the first year. A research carried out by

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