DEVELOPMENT OF ENERGY-EFFICIENT BUILDING ENVIRONMENTAL QUALITY EVALUATION FRAMEWORK

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A thesis submitted in fulfillment of the requirement for the award of the Degree of Master of Civil Engineering

Faculty of Civil and Environmental Engineering
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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.
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LIST OF SYMBOLS AND ABBREVIATIONS

% - Percents
CO₂ - Carbon Dioxide
CVR - Content Validity Ratio
hrs/wk - Hours per week
kW - Kilowatt
kWh - Kilowatt-hour
kWh/m² - Kilowatt hours per meter square
kWh/m²/yr - Kilowatt hours per square meter per year
kWh/year - Kilowatt hours per year
m - Meter
m² - Square meter
MJ - Mega joule
mm - Millimeter
n/2 - number of panelists divided by two
nₑ - 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
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<td>BQA</td>
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<td>BREEAM</td>
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<td>BS5240</td>
<td>Industrial Safety Helmets - specification for construction and Performance</td>
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<td>CBE</td>
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<td>CMC</td>
<td>Chilled Metal Ceiling</td>
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<td>COPE</td>
<td>Cost effective Open Plan</td>
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<td>Car park Energy Consumption</td>
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<td>DCA</td>
<td>Data Centre Area</td>
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<td>DDC</td>
<td>Direct Digital Control</td>
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<td>DTU</td>
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<td>EEBEQ</td>
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<td>EDPM</td>
<td>Electronic Data Processing Machine</td>
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<td>EEMP</td>
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<td>EMS</td>
<td>Energy Management System</td>
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<td>GEF</td>
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<td>GEO</td>
<td>Green Energy Office</td>
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<td>GFA</td>
<td>Gross Floor Area</td>
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<td>Gross Lettable Area</td>
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<td>Human Factors Satisfaction Questionnaire</td>
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<td>HOPE</td>
<td>European Health Optimization Protocol for Energy-efficient buildings</td>
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<td>HVAC</td>
<td>Heating, Ventilating, and Air Conditioning</td>
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<td>ICC</td>
<td>Intra-class Correlation Coefficient</td>
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<td>ICIEE</td>
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<td>KKR2</td>
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<td>KL</td>
<td>Kuala Lumpur</td>
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<td>KLCC</td>
<td>Kuala Lumpur City Center</td>
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<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
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<td>LED</td>
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<td>LEED</td>
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<td>MIT</td>
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<td>MPS</td>
<td>Mapping previous study</td>
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<td>Personal Computer</td>
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<td>Cross-linked polyethylene</td>
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<td>Shading Coefficient</td>
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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
Qahtan et al. (2010) in two energy-efficient buildings in Malaysia show occupants have less satisfaction on the air movement of the building which could be improved through mechanical ventilation.

Different reasons have been suggested in the literature, which include lack of feedback across the building life cycle (Kalay, 2006); and in terms of more technical issues, Augenbroe (2002) suggests that problems in mapping between different tools and procedures may contribute to the low performance of energy-efficient building. Loftness et al. (2009) revealed that significant gaps between the design intent and the performance of buildings and systems over time and occupancy shift could be caused by failures in the design, construction, management or use of buildings. These inefficient building performances can result in occupants’ discomfort.

Occupants’ comfort and comfort-related behavior can impact a building’s energy and environmental performance and lead to the increasing operating energy, particularly in green buildings which are thought to be more fragile in their performance. Sartori & Hestnes (2007) highlighted that reducing the demand for operating energy appears to be the most important aspect for the design of buildings that are energy efficient throughout their life cycle. This is because operating energy represents by far the largest part of energy demand in a building during its life cycle. Therefore, having a building performance analysis which emphasizes on occupants’ comfort particularly towards building’s IEQ is crucial.

Figure 1.0: Building’s performance evaluation perspectives
Leaman, Stevenson, & Bordass (2010) opine that building performance analysis can be studied from three different perspectives such as occupants, environmental performance and economic value as shown in Figure 1.0. Occupants’ perspective towards building performance is focused on how well their needs are met; for the environmental performance, energy and water efficiency are assessed, and; economic value of building is in regard to whether the building makes economic sense, such as value for money or return on investment. Most of the time, client or building owner and designer are more interested in building’s environmental performance and economic value since these two perspectives have a direct impact in reducing the energy cost. According to Vischer (2008), most design and construction decisions involve trading off building quality with construction cost. Thus, occupants’ perspective is often neglected due to its insignificant economic value. Ibrahim (2003) suggested that it is important to ensure building quality and satisfaction of users’ demands and expectations are attended by the design team during the design stage. Therefore, the co-operation between all members of the building design team should be organized to fulfill suitable environment that achieves the satisfaction of the user. Understanding the experience of the building from the occupants’ point of view is as equally important as its technological performance (Leaman, Thomas & Vandenberg, 2007) as shown in Figure 1.1.

Figure 1.1: Occupants’ point of view is equally important as its technological performance

This is because, not only can a poorly performing building affect occupants’ wellbeing and productivity, subsequent measures needed to alleviate occupants’ discomfort can also result in great expense in the building failing to achieve its efficiency targets. According to Hartkopf & Loftness (1999), fulfilling users’ satisfaction in relation to the performance areas of IEQ criteria such as spatial, thermal, acoustics and air quality will be able to create considerably higher quality in
living and work environments, while simultaneously reducing energy and environmental consumption. The key to good building usability is related to good relations between the people and the building, thus usability cannot be evaluated by assessing only physical parameters (Blakstad, Hansen, & Knudsen, 2008).

A fine balance should exist between optimizing energy and resource efficiency in green buildings and providing a comfortable, healthy and productive indoor environment. Fundamentally, green buildings often rely on natural conditioning to meet the comfort needs of end-users, passive strategies are employed to provide indoor conditions that are more able to adapt and link to the variation of temperature according to different season and climate. There are some environmental controls systems that can be designed either to accommodate active user’s engagement, or to intelligently respond and adapt to changing external conditions with minimal user’s engagement. Both approaches share a similarity, that they rely on effective feedback to inform users of design intention and the environmental consequences of their actions. Feedback is particularly important when environmental systems and control are new to designers, operators and users, and matching technological and management capability is crucial (Cohen et al., 1999). Furthermore as occupants demand high performance of energy-efficient design with the aim of improving their comfort, relationship between occupants’ satisfaction and building’s IEQ can be positively correlated with better building performance (Wilkinson et al., 2011).

![Figure 1.2: Correlation between occupants’ satisfaction level towards indoor environmental quality (IEQ) and building performance](image)

According to Ng (2005), there are four types of building performance evaluation methods focusing on occupants’ perspective as shown in Table 1.0. These include Post Occupancy Evaluation (POE), Building in Use Assessment, Building Quality Assessment (BQA), and Total Building Performance (TBP).
Table 1.0: Types of building performance evaluation method

<table>
<thead>
<tr>
<th>Building performance evaluation method</th>
<th>Description</th>
<th>Period of evaluation carried out</th>
<th>Variables of instruments involved</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Post Occupancy Evaluation (POE)</strong></td>
<td>• Post occupancy evaluation is the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time, usually <strong>focused on building’s IEQ</strong> (Preiser &amp; Visher, 2005).</td>
<td>• After occupancy (Preiser, 1995).</td>
<td>• <strong>Standardized questionnaires</strong> (e.g. to staff, business managers, facilities managers, customers); • <strong>Interviews</strong> (e.g. with staff, business managers, facilities managers, customers); • <strong>Observations</strong> (e.g. of staff at work, customers in use of the building); • <strong>Physical monitoring</strong> to provide a set of objective assessments. (Kantrowitz &amp; Farbstein, 1996).</td>
</tr>
<tr>
<td><strong>Building in Use Assessment</strong></td>
<td>• Building-In-Use (BIU) assessment is a systematic rather than an analytical approach of yielding information about people and buildings that can be immediately put to use in solving building problems (Visher, 1989).</td>
<td>• After occupancy (Visher, 1989).</td>
<td>• <strong>Building-In-Use Assessment</strong> comprises a short, <strong>standardized questionnaire</strong> survey of office building occupants (Visher, 2005).</td>
</tr>
<tr>
<td><strong>Building Quality Assessment (BQA)</strong></td>
<td>• Building Quality Assessment (BQA) is a tool for scoring the performance of a building, relating actual performance to identified requirements for user groups in that type of building (Clift, 1996).</td>
<td>• After occupancy (Clift, 1996).</td>
<td>• Evaluated by a <strong>trained assessor</strong> (Clift, 1996).</td>
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</table>
Table 1.0: Continued

<table>
<thead>
<tr>
<th>Building performance evaluation method</th>
<th>Description</th>
<th>Period of evaluation carried out</th>
<th>Variables of instruments involved</th>
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<tbody>
<tr>
<td>Total Building Performance (TBP)</td>
<td>• Total Building Performance (TBP) is a framework, through the comprehensive use of both objective and subjective field evaluations in all performance areas simultaneously, serves to understand the critical balance needed to simultaneously ensure all building performance mandates (Wong &amp; Jan, 2002).</td>
<td>• After occupancy (Wong &amp; Jan, 2002).</td>
<td>• The instruments include a range of tools (interviews, questionnaires, user surveys, checklists, measuring devices, remote probes, indicating and recording devices and computers) which transform a measurable characteristic of the building into information relevant to the building performance (Wong &amp; Jan, 2002).</td>
</tr>
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</table>

From Table 1.0, it can be concluded that POE encompasses the most comprehensive building performance evaluation from occupants’ perspective compared to other methods. The variables of instruments involved in POE are questionnaire, interview, and observation which are related to occupants’ perspective, and the period of assessment carried out is for after occupancy. Besides that, it also focuses on building’s IEQ. Preiser & Vischer (2005) suggested that POE is different from other evaluation methods as it emphasizes on the needs of building occupants. Measures used in POEs include indices related to organizational and occupants’ performance, workers’ satisfaction and productivity, as well as the measures of building performance such as acoustic and lighting levels, adequacy of space, spatial relationships, etc. Hence, by the reasons stated above, POE is the most suitable building assessment method which studies from occupants’ perspective. The importance of the research on POE has drawn researchers’ attention in recent years and has led the development of various types of IEQ survey instruments. From a research done by Peretti & Schiavon (2011), they had identified ten IEQ surveys as shown in Table 1.1.
Table 1.1: Types of Indoor Environmental Quality (IEQ) Survey (Peretti & Schiavon, 2011)

<table>
<thead>
<tr>
<th>Survey name and references</th>
<th>Type of evaluation</th>
<th>Objectives</th>
<th>Investigated topics</th>
<th>Number of applications</th>
<th>Physical measurement</th>
<th>Questionnaire structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUS (Building Use Studies) occupant survey</td>
<td>Long term evaluation</td>
<td>Assess how well buildings work, get feedback on occupants’ needs and perceptions, improve services to occupants</td>
<td>Thermal comfort, perceived comfort, Indoor Air Quality (IAQ), occupant health, productivity (self estimated), personal control</td>
<td>Over 400 organizations and individuals worldwide</td>
<td>Not performed</td>
<td>24 environmental comfort questions, 10 on personal control, 17 on background info, health, productivity, and design.</td>
</tr>
<tr>
<td>HFSQ (Human Factors Satisfaction Questionnaire)</td>
<td>Long term evaluation</td>
<td>Effects of the physical environment on employees’ behavior and attitudes. Survey on satisfaction with the physical environment and job satisfaction</td>
<td>Thermal comfort, IAQ, acoustic quality, structure organization and quality, health and security of occupants. Satisfaction with environmental factors.</td>
<td>N.A.</td>
<td>Not performed</td>
<td>Questionnaire is composed of 42 items</td>
</tr>
<tr>
<td>REF (Ratings of Environmental, Features) questionnaire</td>
<td>Long term evaluation</td>
<td>Research strategies for evaluating facility design, occupants’ productivity, and organizational effectiveness</td>
<td>Thermal comfort, IAQ, acoustic quality, visual quality, and structure layout quality</td>
<td>7 administrative units and offices</td>
<td>Not Performed</td>
<td>Basic Survey: 24 items. Complete survey: 48 items</td>
</tr>
<tr>
<td>Building Assessment Survey and Evaluation (BASE) Study</td>
<td>Long term evaluation</td>
<td>Occupants’ perceptions of IAQ and health symptoms</td>
<td>Workplace physical information, health and well-being, workplace environmental conditions, and job characteristics</td>
<td>100 buildings in 37 cities in 25 US states</td>
<td>Mobile cart: CO₂, temperature, RH, and supply air delivery. Real time monitors: CO, CO₂, temperature, RH, VOCs, PM₂.₅, PM₁₀</td>
<td>33 questions and additional space for comments</td>
</tr>
<tr>
<td>Survey name and references</td>
<td>Type of evaluation</td>
<td>Objectives</td>
<td>Investigated topics</td>
<td>Number of applications</td>
<td>Physical measurement</td>
<td>Questionnaire structure</td>
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<tr>
<td>ASHRAE RP-884</td>
<td>Right-now evaluation</td>
<td>Develop an adaptive thermal comfort standard for ASHRAE</td>
<td>Thermal sensation acceptability and preference, air speed preference</td>
<td>160 buildings, approximately 21,000 subjects</td>
<td>Clothing insulation, metabolic rate, meteorological conditions, indoor air mean radiant temp., air speed, indoor humidity</td>
<td>Background questionnaire and thermal comfort questionnaire</td>
</tr>
<tr>
<td>CBE (Center for the Built Environment-UCB) survey</td>
<td>Long term evaluation with the possibility of right-now problems evaluation</td>
<td>Evaluation of building technologies and performance, quality benchmarking, and diagnosis</td>
<td>Office layout, office furnishings, thermal comfort, IAQ, visual quality, acoustics quality, building cleanliness and maintenance, general satisfaction plus customizable questions (eg. security, etc.)</td>
<td>600 buildings, approximately 60,500 subjects</td>
<td>Depending on which project the measurements are associated with. Level 1 and 2 of the PMP protocol</td>
<td>Core Survey (about 60 questions). Custom modules can be added to address issues not covered in the score questions</td>
</tr>
<tr>
<td>SCATS (Smart Controls and Thermal Comfort)</td>
<td>Right-now evaluation</td>
<td>Correlation between comfort temperatures and indoor/outdoor temperatures, behavioral analyses. Developing an adaptive control algorithm for Europe</td>
<td>Thermal comfort, IAQ, visual quality, acoustic quality, occupant productivity, general comfort</td>
<td>26 buildings in England, Sweden, Portugal, Greece and France. Approximately 4650 subjects</td>
<td>CO2 concentration, globe temperature, air temperature, relative humidity, illuminance, air velocity, noise level, meteorological stations for outdoor parameters.</td>
<td>Transverse questionnaire: 16 questions. Longitudinal questionnaire: 5 questions</td>
</tr>
<tr>
<td>Survey name and references</td>
<td>Type of evaluation¹</td>
<td>Objectives</td>
<td>Investigated topics</td>
<td>Number of applications</td>
<td>Physical measurement</td>
<td>Questionnaire structure</td>
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</tr>
<tr>
<td>COPE (Cost effective Open Plan)</td>
<td>Long term evaluation</td>
<td>Evaluation of indoor environment satisfaction of occupants. How the physical environment influences organizational outcomes (job satisfaction, absenteeism, turnover, productivity)</td>
<td>Thermal comfort, IAQ, visual quality, acoustic quality, privacy, office layout, window access, lighting, work satisfaction, general satisfaction of workstation.</td>
<td>9 buildings</td>
<td>Physical measurements of each participant’s workstation. Cart + chair system (illuminance, air velocity, CO, CO₂, THC, CH₄, TVOC, temperature, RH.)</td>
<td>18 individual Environmental Features Ratings. 27 items in total.</td>
</tr>
<tr>
<td>HOPE Project</td>
<td>Long term evaluation</td>
<td>SBS research, benchmarking of healthy and energy efficient buildings</td>
<td>Thermal comfort, IAQ acoustic quality, occupant health</td>
<td>164 buildings in 98 EU states (69 offices and 95 apartments)</td>
<td>Detailed measurements of chemical, biological and physical parameters</td>
<td>5 comfort items, 7 SBS items and 12 illness indicators</td>
</tr>
<tr>
<td>Remote Performance Measurement, ICIEE-DTU</td>
<td>Long term evaluation with the possibility of right-now evaluation</td>
<td>Evaluation of IEQ satisfaction, health conditions and personal control by occupants. Characterization of occupants’ perceptions and symptoms</td>
<td>Thermal comfort, IAQ, visual quality, acoustics quality, occupant productivity and health (SBS), personal control opportunities, general comfort and satisfaction</td>
<td>Approximately 30 buildings, 1500 people</td>
<td>Depending upon with which project the measurements are associated with</td>
<td>Background questionnaire: occupants’ general perception of indoor environment. Instant Questionnaire: effects on occupants of any intervention performed</td>
</tr>
</tbody>
</table>

¹Type of evaluation: long term evaluation refers to surveys where the aim is to investigate the occupant’s experience (e.g. a week, a month, six month or a year). Right-now evaluation refers to surveys where the aim is to investigate the actual occupants’ sensation)
Although the current IEQ survey instruments for POE are good for grading buildings, they are not inclusive enough when applied on energy-efficient building. The current IEQ survey instruments are unable to directly point out the problems of the building design which causes low performance of IEQ criteria, as the current IEQ survey instruments are not specifically meant for energy-efficient building. Fisk (2001) also argued that studies carried out by PROBE (Building Use Studies (BUS) survey) have failed to tackle all sustainability indicators and occupation styles during reviews.

If a comprehensive building evaluation which encompasses occupants’ perspective is not being conducted to the energy-efficient building, energy-efficient building design team would not be able to easily identify the problems that affect the building performance. Since occupants are the end users of the building, the occupants’ behavior while using the building can directly affect the building performance. Even though the development of energy-efficient building in Malaysia is still at the beginning stage, the industry players such developers, architects, and consultants should focus not only on the development of new energy-efficient building solely but the study on the existing energy-efficient building must not be neglected as well. Owing to this limitation on the POE, a comprehensive evaluation framework is needed in order to reduce the gap between occupants and building’s energy-efficient design. For these reasons, the aim of this research is to determine the comfort level of energy-efficient (office) buildings in Malaysia, and to develop an evaluation framework for the identification of problems in respect to energy-efficient design which affects the occupants’ comfort.

1.3 Research question

In accordance to the above problems, the research questions are as follows:

(i) How is it possible to identify problems affecting the occupants’ comfort in term of energy-efficient design?
(ii) How reliable does the proposed approach in identifying problems affecting the occupants’ comfort in terms of energy-efficient design?

(iii) What is the occupants’ comfort level of the energy-efficient (office) building?

1.4 Research objective

The following objectives are identified in response to the research question:

(i) To propose an evaluation framework for the identification of problems which affect the occupants’ comfort.

(ii) To determine the reliability and validity of the proposed evaluation framework.

(iii) To analyze the occupants’ comfort level of the energy-efficient (office) building.

1.5 Scope of research

The scope of the research is focused on Indoor Environmental Quality (IEQ) criteria of energy-efficient building. The outcomes from the research carried out by Thomas (2010) highlight the importance of improving IEQ for occupants particularly through increased fresh air, daylight, glare control, access to views, and noise management. Thus, the evaluation framework criteria for the energy-efficient design of the buildings are based on the key physical environmental parameters of Indoor Environmental Quality (IEQ) performance; such as thermal comfort, ventilation, lighting, and noise etc.

The studied office buildings are selected from the energy-efficient building in Malaysia. Over the past decade, there is an increasing trend in the development of
sustainable or energy-efficient building in Malaysia. The Ministry of Energy, Green Technology and Water (KeTTHA) building is the maiden energy-efficient building project in Malaysia; the building has even won the 2006 ASEAN building energy awards (Ministry of Energy, Green Technology and Water [KeTTHA], 2006). In the following years, the development of energy-efficient building in Malaysia continues to flourish, the development of the projects, such as Malaysia Green Technology Corporation and Energy Commission building or colloquially known as ST Diamond building are another two showcase energy-efficient building project initiated by the government following the success of the KeTTHA building. Both of the projects have obtained recognition from Malaysian sustainable building rating tools, Green Building Index (GBI) (Green Building Index [GBI], 2011).

Malaysia Green Technology Corporation building was certified with Green Building Index (GBI) certificate; and the ST Diamond building was awarded GBI Platinum and Green Mark Platinum which is the Singapore sustainable building rating tool (Koay, 2011). Although, the buildings have obtained the award and certified by sustainable building rating tools assessment, the efficiency of the building performance is still not at par as the expected performance. One of the Malaysian showcase energy-efficient building projects, Malaysia Green Technology Corporation office building has yet to achieve its desired performance even after three years in operation (Choong, 2009). Thus the proposed survey framework will be tested on the Malaysians’ showcase energy-efficient buildings; the Ministry of Energy, Green Technology and Water (KeTTHA) building and Energy Commission building which are situated in Putrajaya, and Malaysia Green Technology Corporation building located in Bandar Baru Bangi.

According to Peretti & Schiavon (2011), building occupants are a valuable source of information for IEQ. Thomas & Hall (2004) found that good and robust environmental design begins with an integrated design approach that is cognizant of users’ needs and expectations. *Hence, the sampling of research focuses on the occupants of the selected buildings. Random sampling was used to determine the sample size for each selected building*
1.6 Significance of the research

The research is important to the following parties/individuals:

(i) Ministry of Energy, Green Technology and Water (KeTTHA); Energy Commission, and Malaysia Green Technology Corporations as the owner of the building in the effort to improve the efficiency of their energy-efficient buildings respectively.

(ii) Contribute some relevant information regarding current energy-efficient building performance to the parties such as developers who are interested in developing construction projects related to the energy-efficient building.

(iii) Design team (architects or consultants) could use the information regarding the energy-efficient design which affects the occupants’ comfort in preventing the repetition of past mistakes in the future development of energy-efficient building.

(iv) Academicians from civil engineering field could use the newly designed evaluation framework in gathering data regarding IEQ performance for energy-efficient building.

1.7 Structure of thesis

Chapter 1
In the first chapter, the aims, research questions and objectives are identified. The aims and objectives are developed from the identification of problems statement of the research. The needs to design a new environmental quality questionnaire for energy-efficient building are also outlined. Scopes of the research have been identified based on the nature and the requirement of the research. Lastly, significance of the research ended the discussion in Chapter 1, the importance of the
research towards building industry development and engineering field has been justified.

Chapter 2
Chapter 2 is divided into 4 subtopics; energy-efficient building, Indoor Environmental Quality (IEQ), building performance analysis, and post occupancy evaluation. Energy-efficient building subtopic discusses the background and the definition of energy-efficient building, and the energy-efficient designs of the buildings are outlined. Common IEQ criteria problems encountered in energy-efficient building have been identified through previous researches. At the end of the chapter, the importance of implementation of questionnaire survey is justified. The significance of post occupancy evaluation carried out during occupancy stage is also outlined.

Chapter 3
The methodology of the research is divided into three phases; phase 1 involves preliminary study, literature review, and data collection. Phase 2 is regarding the survey framework development. In the second phase, the constructed survey framework EE贝Q validity is determined through content validation and pilot study. After the completion of phase 2, the modified EEBEQ survey questionnaire was tested on the case study building. The results obtained from the survey were then analyzed using sociological validation process, such as criterion validity, construct validity, and intra-class correlation coefficient (ICC).

Chapter 4
Data analysis conducted is detailed in this chapter; the collected data were analyzed according to the methodology procedures stated in Chapter 3. Interview and observation had been conducted while the site visits at the case study buildings had been carried out. Data gathered from previous researches provide important information regarding the problems affecting occupants’ comfort in energy-efficient buildings. The collected data were then computed into questionnaire format EEBEQ. The EEBEQ was tested at the case studies building and its reliability and validity were then being determined thoroughly. The data were collected after questionnaire distributions were conducted, and the results were analyzed using SPSS software.
Detailed discussions are provided in order to examine the credibility of the EEBEQ and to achieve the research objectives.

*Chapter 5*

The research outcomes are summarized in this chapter; the findings of the research are discussed thoroughly. The findings of each objective are also further highlighted and summarized. This process was carried out with the information collected during data analysis. At the end of the chapter, future studies have been proposed for a further development based on current research. A building performance analysis model has been proposed for the designer and the management team of the buildings for a more effective post occupancy evaluation to be carried out in the future.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter the literature review is divided into four parts; (1) energy-efficient buildings, (2) Indoor Environmental Quality (IEQ), (3) building performance analysis, and (4) Post Occupancy Evaluation (POE) method. The study is based on the information gathered from this literature review, which are building performance analysis, POE method, IEQ and energy-efficient buildings.

2.2 Building energy efficiency development

About 40 percent of the global energy consumption is used in buildings and this corresponds to one third of the global greenhouse gas emissions in both developed and developing countries (United Nation Environment Program [UNEP], 2009). Fortunately, the potential for greenhouse gas emissions reductions from buildings is relatively high (Levine et al., 2007). Increasing energy efficiency in buildings is the answer to overcome the unfavorable trend of rising energy consumption. This is because, the energy efficient measures such as energy-efficient building are found to be effective in greenhouse gas emission reduction (Siong, Yun & Morris, 2011).
The concept of energy-efficient building has existed since the early 20th century; the construction of solar houses is one of the efforts towards reducing fossil energy consumption which will ultimately contribute to reduced greenhouse gas emission. The construction of the solar houses aims to realize zero fossil energy consumption in buildings heating systems. One of the examples of solar house is MIT Solar House I as shown in Figure 2.1. The solar house was built in 1939 and it is located at Cambridge, Massachusetts, United States. The solar house includes solar thermal collecting area and water storage system (Butti & Perlin, 1980). In 1955, the solar technology had been applied in the Bliss House located at Melbourne, Florida, United States; the solar technology has been used in the ventilation system (Bliss, 1955).

![Image of MIT Solar House I](Artists Domain, 2010)

Figure 2.1: MIT Solar House I located at Cambridge, Massachusetts, United States

Another example of energy-efficient building is zero energy building (ZEB). In 1975, Professor Korsgaard from Danish Technical University together with his colleagues had successfully built a Zero Energy House (ZEH) at Thermal Insulation Laboratory. The building is the first solar heated house in northern Europe (Esbensen & Korsgaard, 1977). Following the success of ZEH in Denmark, many countries have started to develop their own energy-efficient buildings.

These early examples have been influential in current approaches to building design and indeed contributed to the definition and upgrade of building standards and regulatory codes. At present, voluntary standards for low-energy buildings using the principles of high insulation, good air tightness and heat recovery ventilation systems are increasingly popular, such as the scheme R-2000 in Canada (Natural Resources Canada, 2005), and Passivhus.dk a consulting company responsible for certifying...
passive house in Denmark (Passivhus.dk, 2012). This trend is now extending to other parts of the world.

The importance of reducing building energy consumption has elevated the development of energy-efficient building; each country has its own definition and standard to classify energy-efficient buildings. The variables of definitions and standards can be due to the different in climates and economy state of each country. Nevertheless, the approaches and guidelines by each party should contribute towards reducing building energy consumption and greenhouse gas emission by any means.

2.3 Definition of energy-efficient building

There is no specific definition for energy-efficient building whether in academic studies or at national levels. Each country in Europe has different definitions and scopes for energy-efficient building (Thomsen & Wittchen, 2008). However, its term could be traced from the previous research which related to energy-efficient building. In this section a definition of energy-efficient building will be derived from the summary of the previous researches related to the term of energy-efficient building used by researchers from various studies and fields.

Hauge et al. (2010) define energy-efficient building as building made to reduce energy consumption to different degree that includes low-energy buildings, passives houses, LEED buildings, and green buildings. Another research done by Zhang & Leimer (2011) entitled Low Energy Certificate – An Exploration on Optimization and Evaluation of Energy-efficient Building Envelope, refer green building as energy-efficient building. Furthermore, according to Kropf & Goricanec (2009), the awareness of the importance of energy efficiency of building has brought to the development of energy-efficient (saving) building, and it includes low energy buildings, 3 liters house, passive house, zero-energy house, energy self-sufficient house, and plus-energy house. Thormak (2001), conducts a research to analyze the recycling potential of a low-energy dwelling (45 kWh (162 MJ) = m²) in Sweden. In the research, the low energy building and passive houses are referred as energy-efficient building. In addition, Bauer & Scartezzini (1997), in their research on a simplified correlation method accounting for heating and cooling loads in energy-
efficient buildings, one of the studied buildings is a simulated passive solar office room. According to Carassus (2008) energy-efficient buildings could be classified into three types of models: the Low Consumption model (eg. Passivhaus in German), the Energy and Environmental model (eg. LEED certified building) and the Energy Saving and Production model for example Zero Energy Homes.

While, a research conducted by Ahmed et al., (2009) in regard to the analyze of building performance data for energy-efficient building operation. During the research they have selected an energy-efficient building with many sustainable energy features such as solar panels, geothermal heat pumps and heat recovery systems as case study building. On the other hand, Kim et al. (2010) do an analysis of energy efficient building design through data mining approach. In their research, the energy-efficient building design for the building includes the building location, envelope (walls, windows, doors, and roof), heating, ventilation and air conditioning (HVAC) system, lighting, controls, and equipment. Kantrowitz (1984), carried out a research on energy-efficient building, describes energy-efficient building is a building designed with energy-efficient design such as HVAC and lighting system.

Based on the research done in previous studies, it is found that the researchers tend to form a collective agreement between one another in terms of their understanding of energy-efficient building. Energy-efficient building can be defined as a building using energy-efficient design strategies in reducing its energy consumption in order to achieve low energy consumption. It includes zero energy building, passive house, low energy building, LEED buildings, green buildings, energy self-sufficient house, plus-energy house and any other buildings that have been specifically designed with the aim of achieving energy-efficiency.
2.4 The variable of terminology for building with energy efficiency features

2.4.1 Zero energy building

According to Torcellini et al. (2006), zero energy building (ZEB) is defined as a residential or commercial building which greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies. In 1975, Professor Korsgaard from Danish Technical University has successfully built a Zero Energy House (ZEH) at Thermal Insulation Laboratory as shown in Figure 2.2. The building is the first solar heated building built in North Europe (Gram-Hansen & Jensen, 2005).

![A ZEH at Danish Technical University, Lyngby, Denmark (Seifert, 2006)](image)

Figure 2.2: A ZEH at Danish Technical University, Lyngby, Denmark (Seifert, 2006)

2.4.2 Passive house

Passive House concept is based on a holistic approach, improving the building envelope to a degree that allows for substantial simplifications of the heating system. Passive Houses offer increased comfort at affordable costs while significantly reducing the energy consumption (Feist et al., 2005). This concept was developed in Germany in May 1988 by Bo Adamson and Wolfgang Feist, and has since then been widely and successfully used in Germany and Austria (as cited in Janson, 2008). One of the examples of passive house is the Passive House in Darmstadt.
Kranichstein (Figure 2.3) which has been constructed in 1990/91 on design plans by a team of architects, Prof. Bott/Ridder/Westermeyer, for four private clients (Steinmüller, 2008).

![Passive House in Darmstadt Kranichstein](image)

Figure 2.3: Passive House in Darmstadt Kranichstein (Feist, 2006)

### 2.4.3 Low energy building

Low-energy building or simply low-energy refers to a building built according to special design criteria aimed at minimizing the building’s operating energy (Sartori & Hestnes, 2006). According to European Commission (2009), low-energy buildings typically use high levels of insulation, energy efficient windows, low levels of air infiltration and heat recovery ventilation to lower heating and cooling energy. They may also use passive solar building design techniques or active solar technologies. The office building SD Worx as shown in Figure 2.4, is a low energy building which is located in Kortrijk, Belgium and consists of two office floors on top of a limited ground floor with building services (Breesch et. al., 2004).

![SD Worx, Kortrijk, Belgium](image)

Figure 2.4: SD Worx, Kortrijk, Belgium (Breesch et. al., 2004)
2.4.4 Green building

According to Burnett (2006), green building is a building that provides the specified building performance requirements while minimizing disturbance to and improving the functioning of local, regional, and global ecosystems both during and after its construction and specified service life. Moreover, optimizes efficiencies in resource management and operational performance; and minimizes risks to human health and the environment. Genzyme Corporation as show in Figure 2.5 is a world-class example of green building construction, including advanced daylighting and thermal technologies. The building obtained LEED-Platinum due to its high efficiency and environmentally responsive architecture (Lockwood, 2006).

![Figure 2.5: Genzyme Corporation Headquarter, Cambridge, Massachusetts, USA (Kats, 2003).](image)

2.4.5 Energy self-sufficient house

One of the prominent examples of energy self-sufficient house is the Self-Sufficient Solar House (SSSH) in Freiburg, Germany (Figure. 2.6), built by the Fraunhofer Institute for Solar Energy Systems. Its entire energy demands for heating, domestic hot water, electricity and cooking is supplied solely by solar energy (Voss et al., 1996). According to Krope & Goricancic (2009), energy self-sufficient house is capable to generate energy for heating, cooking, water heating and the operation of home appliances through active utilization of solar energy.
REFERENCES


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